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TRANSMISSION OF POWER

BY

WIRE ROPES.

BY

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Member American Society of Mechanical Engineers.

Second Edition, Revised.

NEW YORK:

D. VAN NOSTRAND COMPANY,

23 MURRAY AND 27 WARREN STREET.

1889.

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PREFACE.

SINCE this little volume was first published, twelve years ago, the question of the economical transmission of power has become one of prime importance.

Central stations have been established for the cheap production of power in large quantities, and the distribution of the same over considerable areas to thousands of consumers. The present tendency is toward still further centralization of the production of power, and its transmission to any required points.

While such extraordinary efforts are being made to cheapen the actual production of power, great care must be exercised that no unnecessary losses be sustained during its transmission. For many years, rapidly moving wire ropes

were undoubtedly the most efficient means of conveying power to great distances; but the rapid strides which have been made in the development of electrical transmission have limited the field of the useful application of wire ropes. There are, however, certain limits between which the transmission of power by wire ropes is yet more efficient than by any other methods; and these limits we will attempt to define.

The literature on this subject, especially in the English language, is very limited. Much of the practical part of the subject is well handled in the report of the U. S. Commissioners to the Paris Exposition of 1867, and in pamphlets published by the J. A. Roebling's Sons Co., the Trenton Iron Co. and several other firms engaged in the manufacture and installation of such plants.

In Europe, where this method of transmitting power had its origin, its theory and practice have been investigated by Prof. F. Reuleaux, who has devoted a number of chapters to it in his various scientific works, and by Prof. W. C. Un-

win, in his "Elements of Machine Design." It has also been extensively written on by Mr. D. H. Ziegler, of the firm of J. J. Rieter & Co., Switzerland, who have long been identified with such work.

It is to the publications above mentioned that much of the matter in the following pages is due.

TRANSMISSION OF POWER BY WIRE ROPES.

THE fundamental problems of mechanical engineering are those relating to the generation, transmission, and utilization of power. But not all of these have hitherto received the same degree of attention; and it is a well-known historical fact that economy in the generation of power in the prime mover, and economy in its utilization in the machine, have in most countries been far in advance of its economical transmission from the one to the other.

Improvements in steam-engines and boilers, in hydraulic engines, water-wheels, and turbines, and in air, gas, and oil engines, have come in rapid succession, until there seems but little room for further advance in this direction;

and at the same time our machines and machine tools have been rapidly approaching a state of comparative perfection. But only in recent years has it been thought worth while to bestow much care and attention on the economical transmission of the energy from the prime mover to the machine.

Not many years ago this transmission of power was accomplished by means of cumbersome wooden shafts, upon which were wooden drums for the driving-belts; gearing also made of wood; slow-moving, awkward contrivances for the purpose, and very wasteful of power. This stage is now happily passed, and the distribution of power to short distances is accomplished with but little waste, by rapidly moving belts, and light steel shafting running in accurately fitted journals.

In addition to the usual cases of short-distance transmission, there are two large classes of cases where the distance enters as a most important factor: the one comprises all those cases where the power of hitherto inaccessible sources of natural energy is to be transmitted to

distant points, where it can be usefully employed; and the other comprises all those cases where the source of energy is itself accessible, but where it is desired to distribute the power to a number of independent small working centres.

Although among the most efficient means of transmitting power to short distances, both belting and shafting have the disadvantage that, when the distance becomes great, the intermediate mechanism absorbs an important portion of the power by vibrations, friction, and resistances of every nature; and for a distance of several hundred feet we do not get, at one end of the transmission, more than an extremely small fraction of the power applied to the other; thus, a shaft one mile long would transmit only about one half the energy imparted to it; while a shaft two miles long, running in well made and lubricated bearings, would absorb the entire power in friction: in other words, no amount of power would suffice to turn it.

In the case of a mere dead pull, as in working a pump, work is and has long

been transmitted to great distances; as, by the long lines of "draw-rods" used in mining-regions to transmit the power of a water-wheel by means of a crank on its main axis, pulling, during half its revolution, against a heavy weight, and thus storing up energy for the return stroke, as the rods, on account of their flexibility, cannot be used to exert a pushing strain. Rotary motion, however, cannot be economically produced in this manner.

Of late years, much attention has been bestowed on the various means of transmitting power to distances; and each has been brought to a considerable degree of perfection.

Four such methods are now in use, and have each their well-defined sphere of action. Thus we may transmit energy by means of electricity or wire ropes, or by hydraulic or pneumatic connection. As we shall see later, the great expense of the plant for the latter two methods, as well as their low efficiency due to friction in the pipes, precludes their use except where special local circumstances

render their other advantages of more importance than the question of economy. The real competition, then, lies between electricity and wire ropes ; and where economy is the only feature to be considered, the point on either side of which one or the other of these systems is preferable is fairly well defined.

The undisputed credit of inventing the use of wire ropes for the transmission of energy belongs to the Hirn Brothers, of Mülhausen, Switzerland.* To satisfy themselves on this point, the International Jury at the Paris Exposition in 1867 made a thorough search through the registers of patents and other publications for many years, but failed to find anything bearing the least resemblance to this method.

The principles underlying the transmission of power by wire ropes are :

(1) The mechanical work done in any given time is equal to the resistance overcome, multiplied by the distance through which the resistance is overcome;

* See "Notice sur la transmission telodynamique, par C. F. Hirn (Colmar, 1862)."

(2) In the performance of mechanical work, force may be exchanged for velocity, or velocity for force.

To illustrate, let us suppose a bar of iron, having a cross sectional area of one square inch, to move endlong at the rate of two feet per second. If the resistance overcome is, say, 5000 pounds, work will be performed at the rate of 10,000 foot-pounds per second. Now, if we double the velocity of the bar, we will transmit twice the amount of work with the same strain, or the same work may be transmitted with only half the former strain. Supposing the proper intensity of tension in the bar to be 5000 pounds per square inch, we may thus, at this double velocity, transmit the same original amount of work by a bar having an area of only half a square inch. In a similar manner, if we move the bar with the velocity employed in wire-rope transmission, viz., about eighty feet per second, then, while doing the same amount of work, the strain on the bar will be reduced from 5000 to 125 pounds; and to maintain a tension of 5000 pounds

per square inch, the bar will only need a section of 0.025 square inch. To put an extreme illustration, we may conceive of a speed at which an iron wire as fine as a human hair would be able to transmit the same amount of work as the original one-inch bar.

By the application of these simple principles in Hirn's apparatus, energy is thus transmitted in the shape of considerable velocity and little force, while at the receiving-station it is again converted back into the generally more useful form of large force and little velocity.

MECHANICAL DETAILS.

THE construction of the apparatus is very simple. A tolerably large iron wheel, having a V-shaped groove in its rim, is connected with the motor, and driven with a perimetral velocity of usually from 50 to 100 feet.

Round this wheel is passed a thin wire rope, which is led away to almost any reasonable distance (the limit being measurable by miles), where it passes over a similar wheel, and then returns as an endless band to the wheel whence it started.

The peripheries of the driving-wheels may have an angular velocity as great as convenient; the only limit, in fact, being that the speed shall not be so great as to involve any danger of destroying the wheels by centrifugal force. The speeds which have been actually employed in practice vary from 25 to 100

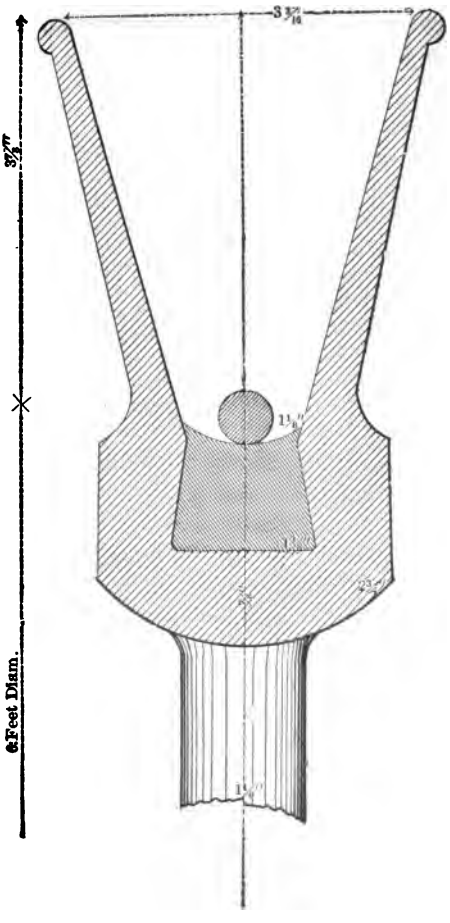
feet per second at the circumference of the pulley.

The Wheels. — The wheels themselves are made as light as is consistent with strength, not only for the sake of reducing the friction on the journals of their shafts to a minimum, but for the equally important object of diminishing the resistance of the air. It can hardly be doubted that abandoning spokes entirely, and making the pulley a plain disc, would considerably improve the performance, could such discs be made at once strong enough to fulfil the required functions, and light enough not materially to increase the friction.

The wheels are usually made of cast-iron or steel, and, beside their lightness, have but one peculiarity of construction, and that is a highly important one: at the bottom of the V-shaped groove, going around the circumference, a little trough is formed, in which the filling is placed, as shown in Figs. 1 and 1*a*.

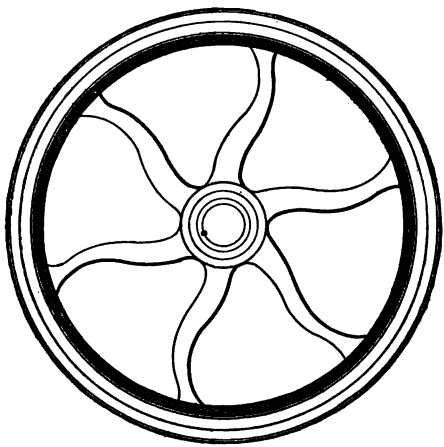
The materials used for this filling are many in number, and will be discussed

Fig. 1.



further on. The rope should always run on a filling of some kind, and not directly on the iron, which would quickly wear it out.

Fig. 1a.



For wheels of over 14 feet diameter, the wrought-iron construction shown in Fig. 1*b* is probably the best, combining lightness and strength; but wheels of such large size are not usually found necessary.

Fig. 1 b.

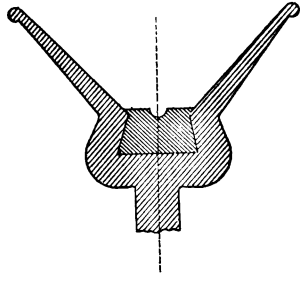
The rope is not tightly stretched over the wheels, but, to all appearances, hangs loosely on the same. But the rope does not slip, as the tension caused by its own weight presses it hard against the rims of the wheels if the latter are of proper size. The body of the driving-wheel (Fig. 1*a*) differs very little from that of a belt-pulley; and it can always be proportioned as a belt-pulley, having to transmit the same power with the same velocity.

The sides of the rim are usually made to slope about 25° to 30° from the vertical (Fig. 1). This slope, if used in a double wheel, such as are used at intermediate stations, would give an extremely heavy central rib, on which account the sides of the latter are usually made steeper, viz., about 15° from the vertical.

Even when the greatest care is taken in the installation and maintenance of a transmission, it seems impossible to prevent more or less oscillation and swinging of the ropes against the sides of the wheel-rims, resulting in rapid wear of the

ropes. This evil may be to a great extent remedied by making the section of the wheel rim more as shown in Fig. 1*c*, flaring out the sides at angles of 45° with the vertical. This would be specially beneficial where the ropes are exposed to

Fig. 1 c.



a high side wind, but is attended with several disadvantages, particularly in the case of double-grooved wheels (compare Figs. 1*d* and 1*e*). The difficulty and expense of making the wheels would be greater, and the increased distance between the ropes would result in considerable side pressure on the bearings of the shafts.

Wheels from about nine feet in diame-

Fig. 1 d.

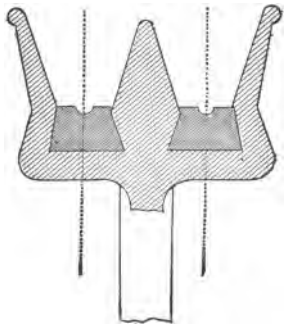
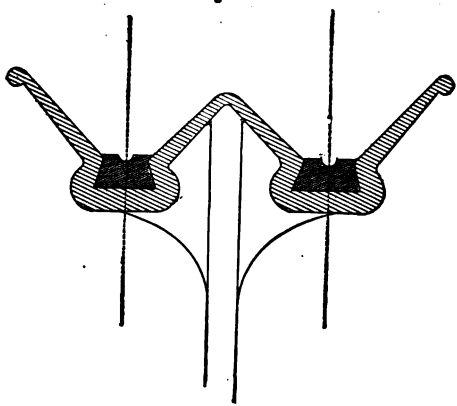


Fig. 1 e.



ter up are usually cast in halves and afterward fastened together on the shaft. In order that the centrifugal force may not become dangerous, the perimetral velocity should not exceed 90 to 100 feet per second. Velocities up to 90 feet have been frequently used without any prejudicial results whatever. Owing to the high speed employed, it is absolutely essential that the wheels should be perfectly balanced.

The filling first employed by Mr. A. Hirn consisted of a strong leather belt covering the rim and fastened to the same by nails and wooden wedges, as shown in Figs. 2 and 3.

With wheels of large diameter, he was obliged to make this belt of several pieces, thereby weakening it considerably. This style of filling, however, rarely lasted longer than a few months. Hirn was then induced to try rubber ; but with very large wheels, the rubber was found to be unsuitable on account of its great expansion when heated, so that when wheels filled with it were exposed to the direct and strong rays of the sun,

the rubber became soft and was cut by the rope, or it expanded over the edge of the wheel, causing the rope to be thrown

Fig. 2.

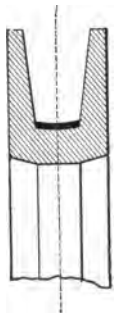
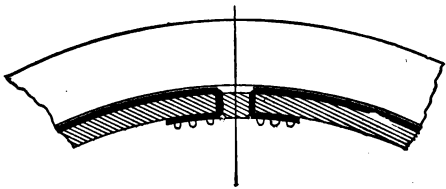


Fig. 3.



off. In some cases, where the filling expanded greatly at noon, it returned to its original position during the night. On the other hand, there are cases

known when in cold nights, during the stoppage of the transmission, the rope would freeze to the rubber filling. On starting in the morning, large fragments of the brittle rubber were torn out. Besides this, the rubber was also slowly dissolved by the oil and grease on the rope.

After some unsuccessful attempts at filling with hippopotamus-skin, willow and poplar wood were tried, giving quite passable results. Strips of poplar wood about $\frac{1}{8}$ inch thick and 7 to 10 feet long were planed to the proper section, softened in hot water, and then driven in without any special fastening. This process was very simple, allowing the wheels to be refilled quickly and at slight expense. The main difficulty was that the filling sometimes became loose, owing to the drying and shrinking of the wood during the hot season. This was partly prevented by driving pieces of wire through the filling and the rim of the wheel. The wood was also softened in hot glycerine instead of hot water, thus rendering it less subject to the varying hygrometric condition of the air. In

spite of these precautions, a wooden filling rarely lasted more than six or nine months when the wood was most carefully selected, while, if knots or unsound spots were present in the filling, it wore out in a still shorter period. Various other woods were then tried, but willow and poplar were found to be the most durable as well as the cheapest.

As wood wears less when subjected to strain and pressure across the direction of the grain, this method was also tried, notably at the Schaffhausen Water-works. In this case, small pieces were cut, having the fibre running from side to side of the rim of the wheel. These pieces were then dried thoroughly, and frequently immersed in linseed varnish until they were completely saturated with the latter, thus becoming more durable and air-tight. Notwithstanding these precautions, some of the pieces became loose, and, although more durable than the plain wood filling previously described, they did not last longer than about one year. A further trial was made with wood filling in which the fibres ran radially, but with no better

results. But this last method has the advantage that, when the rope wears a groove into the wood, the sides do not split off as easily as in the two other styles.

Cork has also been tried to some extent, but it has proved of little value for transmitting any considerable force, as it wears out very rapidly.

Again, by wedging the groove full of tarred oakum, a cheap filling was obtained, nearly as good as leather, and not so tedious to insert.

Another plan was to revolve the wheel slowly, and let a lot of small-sized tarred ratlin or jute yarns wind up on themselves in the groove. After a day or two of running, the pressure of the rope, together with the tar, made the filling compact.

The first attempts with radial leather filling were made about 1865 ; and it was soon found that this method of filling was so decidedly superior to all others that it has now come into almost exclusive use. It is easily inserted by any ordinary mechanic. The separate pieces of

leather are driven hard against each other in the groove of the wheel, which has been carefully turned true. The key or closing piece is made of india-rubber, which is first softened in hot water and then driven into its proper place. The greatest wear of the filling occurs not, as might be expected, in the driving-wheels, but in the intermediate carrying-sheaves, and there principally in the smaller wheels.

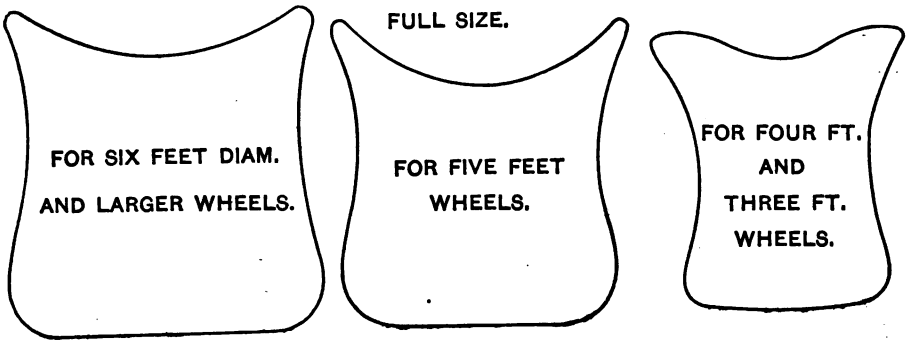
The life of leather filling depends on the quality of leather used, and on the radial thickness of the pieces. It is also affected by the tension, and general condition of the ropes. It may usually be estimated at about three years.

Lately a new kind of hard rubber filling has come into extensive use, and seems to be meeting with considerable success. The shape of the filling is shown in the full-size sketches on page 28.

A convenient method of lining the inside faces of the flanges of transmission wheels is illustrated in Fig. 4. Segments of sole-leather, *B*, are secured

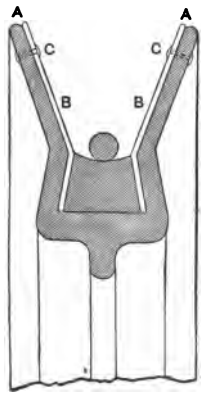
FILLING FOR TRANSMISSION WHEELS.

FULL SIZE.



to the flange, *A*, by rivets, and thus the rope, in applications where it is exposed to side winds inducing lateral swaying, is

Fig. 4.



protected from wear upon the sides of the rim.

The following table gives the usual weights and prices of transmission wheels (Figs. 1 and 1*a*) with hub bored to required size, and furnished with either rubber or leather filling:

TRANSMISSION WHEELS.

Diameter in Feet.	Weight in Pounds.	Price per Wheel.
1½	....	$ 7
2	....	8
3	....	20
4	400	28
5	685	40
6	950	65
7	1100	80
8	1400	110
9 } cast in	1680	190
10 } halves	2300	210

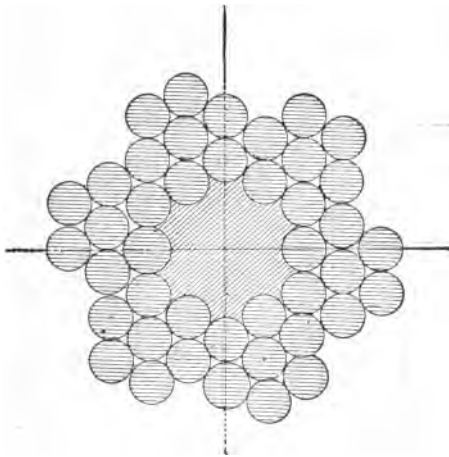
The price of wheels such as shown in Fig. 1*b* would be: 14 ft. diameter, about $350; 16 ft. diameter, about $400.

There is usually a trade discount, from above prices, of from 5 to 10 per cent.

Additional rubber or leather filling is sold at about 60 cents per pound.

The Ropes.—The driving-rope usually employed in this country consists of six strands, with seven iron or steel wires to each strand (Fig. 5). The strands are spun around a hempen centre or core, thus obtaining the necessary flexibility.

Fig. 5.



If d = diameter of wire in inches;
D = diameter of rope in inches;
w = weight of rope in pounds per running foot,—
then for this kind of rope
$D = 9\ d$;
$w = 1.5\ D^2$ (very nearly).

The following table gives further particulars concerning the above rope, representing the practice of the principal American

firms engaged in the business of making such installations:

WIRE ROPE

CONSISTING OF 6 STRANDS OF 7 WIRES EACH.

IRON.

Trade No.	Diameter in inches.	Price per foot.	Estimated Weight per foot, in pounds.	Breaking Stress, in tons of 2000 lbs.	Proper Working Load in tons of 2000 lbs.
11	1½	$0.48	3.37	36.0	9
12	1⅜	.39	2.77	30.0	7½
13	1¼	.34	2.28	25.0	6¼
14	1⅛	.27	1.82	20.0	5
15	1	.23	1.50	16.0	4
16	⅞	.19	1.12	12.3	3
17	¾	.14	0.88	8.8	2¼
18	⅝	.12	0.70	7.6	2
19	⅝	.10½	0 57	5.8	1½
20	½	.08	0.41	4.1	1
21	⅜	.07	0.31	2.88	¾
22	⅜	.05½	0.23	2.13	½
23	⅜	.05	0.19	1.65	....
24	¼	.04	0.16	1.38	....
25	¼	.03½	0.125	1.08	....

SPECIAL CAST-STEEL.

11	1½	$0.70	3.37	88.38	22.0
12	1⅜	.60	2.77	67.20	16.8
13	1¼	.50	2.28	60.67	15.2
14	1⅛	.40	1.82	39.84	10.0
15	1	.32	1.50	31.82	8.0
16	⅞	.25	1.12	24.70	6.2
17	¾	.19	0.88	18.48	4.6
18	⅝	.16	0.70	16.32	4.0
19	⅝	.14	0.57	12.44	3.1
20	½	.11	0.41	9.33	2.3
21	⅜	.08	0.31	6.89	1.7
22	⅜	.07½	0.23	5.23	1.3
23	⅜	.07	0.19	3.93	1.0
24	¼	.05	0.16	3.25	.81
25	¼	.04½	0.125	2.96	.75

Fig. 5 a.

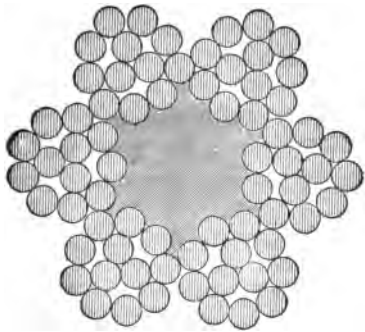
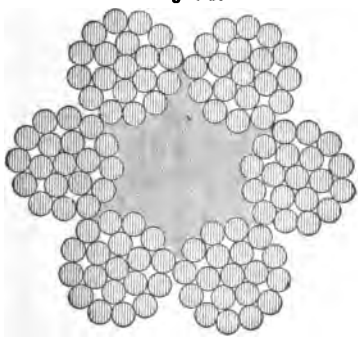


Fig. 5 b.



For cases where unusual conditions compel the use of specially small wheels, it is better to employ one of the more flexible ropes shown in Figs. 5*a* and 5*b*, for which the formulæ subsequently to be given can be readily modified.

The following table gives particulars concerning the rope shown in Fig. 5*b*.

WIRE ROPE

CONSISTING OF 6 STRANDS OF 19 WIRES EACH.

IRON.

Trade No.	Diameter, in inches.	Price per foot.	Estimated Weight per foot, in pounds.	Breaking Stress, in tons of 2000 lbs.	Proper Working Load, in tons of 2000 lbs.
1	2¼	$1.00	7.75	74.00	15
2	2	.78	6.11	65.00	13
3	1¾	.69	5.09	54.00	11
4	1⅝	.58	4.00	44.00	9
5	1½	.53	3.55	39.00	8
5½	1⅜	.43	2.90	33.00	6½
6	1¼	.36	2.42	27.00	5½
7	1⅛	.29	1.95	20.00	4
8	1	.26	1.53	16.00	3
9	⅞	.20	1.16	11.50	2½
10	¾	.16	0.85	8.64	1¾
10¼	⅝	.14	0.60	5.13	1¼
10½	½	.12	0.47	4.27	¾
10¾	⅜	.10	0.37	3.48	½
10⅞	⅜	.08	0.26	2.50	¼

SPECIAL CAST-STEEL.

1	2¼	$1.52	7.75	164.69	32.90
2	2	1.20	6.11	132.37	26.50
3	1¾	1.00	5.09	108.13	21.63
4	1⅝	.80	4.00	97.17	19.44
5	1½	.71	3.55	86.38	17.30
5½	1⅜	.60	2.90	72.33	14.46
6	1¼	.50	2.42	50.17	10.00
7	1⅛	.41	1.95	38.00	7.70
8	1	.34	1.53	29.20	5.80
9	⅞	.27	1.16	21.55	4.00
10	¾	.21	0.85	14.99	3.00
10¼	⅝	.18	0.60	12.53	2.50
10½	⅝	.17	0.47	8.81	1.75
10¾	½	.15	0.37	7.52	1.50

The Special Cast-Steel Rope is made from wire manufactured for the purpose, of high tensile strength (about 175,000 pounds per square inch of section), and at the same time of exceptional toughness and ductility.

There is usually a trade discount, from prices given in above tables, of 25% to 35% on iron ropes and about 45% on steel ropes.

In splicing a wire rope, the greatest care must be taken to leave no projecting ends or thick parts in the rope. On this subject, I can do no better than give Messrs. Roebling's directions for making

a long splice in an endless running rope of half-inch diameter:*

"Tools required: One pair of nippers, for cutting off ends of strands; a pair of pliers, to pull through and straighten ends of strands; a point, to open strands; a knife, for cutting the core; and two rope-nippers, with sticks to untwist the rope; also a wooden mallet.

"*First.*—Heave the two ends taut with block and fall, until they overlap each other about twenty feet. Next, open the strands of both ends of the rope for a distance of ten feet each; cut off both hemp cores as closely as possible (Fig. 6), and then bring the open bunches of strands face to face, so that the opposite strands interlock regularly with each other.

"*Second.*—Unlay any strand, *a*, and follow up with the strand 1 of the other end, laying it tightly into the open groove left upon unwinding *a*, and making the twist of the strand agree ex-

* See "Transmission of Power by Wire Ropes," by W. A. Roebling, C.E.

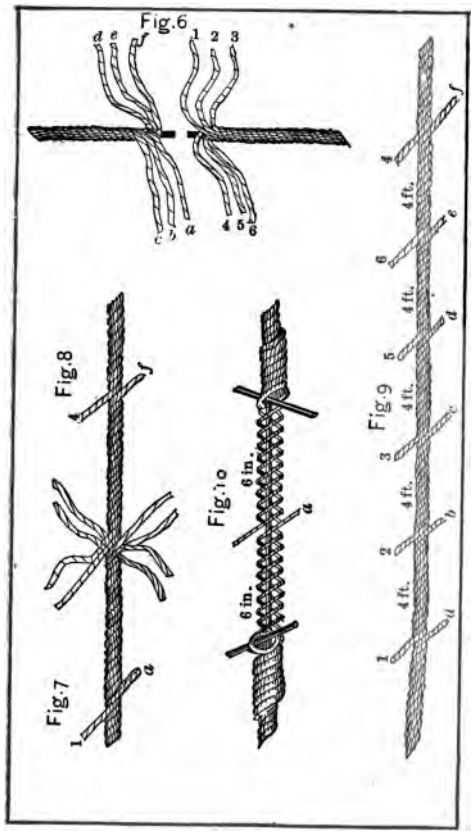


Fig.6
Fig.7
Fig.8
Fig.9
Fig.10
6 in.
6 in.
4 ft.
4 ft.
4 ft.
4 ft.
4 ft.

actly with the lay of the open groove, until all but about six inches of 1 are laid in, and *a* has become twenty feet long. Next cut off *a* within six inches of the rope (Fig. 7), leaving two short ends, which must be tied temporarily.

"*Third.*—Unlay a strand, 4, of the opposite end, and follow up with the strand *f*, laying it into the open groove, as before, and treating it precisely as in the first case (Fig. 8). Next, pursue the same course with *b* and 2, stopping, however, within four feet of the first set; next with *e* and 5; also with *c*, 3 and *d*, 4. We now have the strands all laid into each other's places, with the respective enes passing each other at points four feet apart, as shown in Fig. 9.

"*Fourth.*—These ends must now be secured and disposed of, without increasing the diameter of the rope, in the following manner: Nipper two rope-slings around the wire rope, say six inches on each side of the crossing-point of two strands. Insert a stick through the loop and twist them in opposite directions, thus opening the lay of the rope (Fig.

10). Now cut out the core for six inches on the left and stick the end of 1 under *a*, into the place occupied by the core. Next, cut out the core in the same way on the right, and stick the end of *a* in the place of the core. The ends of the strands must be straightened before they are stuck in.

Now loosen the rope-nippers and let the wire rope close. Any slight inequality can be taken out by pounding the rope with a wooden mallet.

"Next, shift the rope-nippers, and repeat the operations at the other five places.

"After the rope has run for a day, the locality of the splice can be no longer detected. There are no ends turned under or sticking out, as in ordinary splices, and the rope is not increased in size nor appreciably weakened in strength."

I have dwelt so minutely on the process of splicing, because practical experience has demonstrated that a man who can splice a wire rope well is something of a rarity. Some of the best ship-riggers are utterly nonplussed when a wire

rope is presented to them to be spliced; and the splice they produce is usually half again as thick as the rope, and utterly useless for the intended purpose.

Wire ropes with *wire* centers are sometimes employed for the transmission of power, but they have not usually proved satisfactory in practice, wearing out much more rapidly than ropes with *hemp* centers. The only advantage to be gained by the use of wire rather than hemp centers is in the increased strength of the ropes, enabling a certain amount of power to be transmitted with a smaller rope, and in the fact that such ropes stretch less than those with hemp centers.

This latter difficulty can be almost entirely obviated, as will be explained further on; and as the ropes with hemp centers are much more durable, they are now used almost exclusively. Another disadvantage found in the use of ropes with wire centers is that the splice must be made nearly twice as long as when hemp is used for the center. This must be done to prevent the two ends of the

rope from slipping out, as the coefficient of friction is not so great between iron and iron as between iron and hemp.

As, in splicing, the wire center is cut off at the splice and not spliced in, it is free to move in the rope in the direction of least resistance. It consequently happens that the wire center frequently protrudes through the strands of the rope. This may be partly remedied by sewing with cord through the center and the outside wires, thus fastening them in their proper relative positions. In a short time, however, the center will again project; we are then compelled to cut off the projecting end, and repeat the operation of sewing with cord, which does not by any means improve the durability of the rope. The principal difficulty—the excessive wear of the outer wires—is common to both kinds of ropes. This wear is caused chiefly by the friction of the wire on the sides of the wheel-groove when the rope for any reason runs unsteadily and swings against the sides of the groove. The ropes get flat in places and finally the wires break.

It is difficult to lay down any general rule as to the duration of the ropes, for this depends on the conditions under which they work. In ordinary practice, about one year can be safely counted on; and although the ropes will usually last considerably longer, it is customary to replace them before they finally give out, to avoid interruption in the work. If duplicate ropes are kept on hand ready, and spliced to the proper length, and if a short interruption of the transmission is not of much moment, the ropes may be run until they are actually worn out, and will in such cases probably average a life of nearly two years.

To prevent the wear of the wires, and thus to make the ropes more durable, has been the object of several inventions; all of which were attempts at surrounding the wires with a flexible and durable covering, protecting the wires, and at the same time not increasing the difficulties of splicing. It was also thought that, if this could be made a practical success, the filling in the wheels might be entirely dispensed with. Instead of

the rope running on the soft filling of the wheel, the soft envelope of the rope might run directly on the cast-iron rim. Nearly all the experiments in this direction have failed, and it is only recently that the firm of Martin Stein & Co., Mülhausen, Switzerland, have partially solved this problem. They have for some time been making ropes in which coarse cot'on yarn was spun about the separate wires, the latter being then spun into rope. In this way they obtain a soft body between the separate wires, and also a soft envelope for the whole rope, which, when saturated with a special resinous compound, is said to be very durable. The rope also seems less affected by variation of weather, being partly protected against sun and rain by the covering. For the same reason, rusting is not so likely to occur. If, in connection with these covered ropes, wheels with leather filling were employed, the adhesive force on the pulleys would become much greater than with the ordinarv ropes, thus reducing the necessary tension in the ropes. These ropes have not come into use in

this country; and only experience will determine whether their durability is sufficient to warrant their more general introduction.

The price of such covered wire ropes is naturally greater than that of ordinary wire ropes; but if, as the manufacturers claim, they may be expected to last about three times as long as ordinary wire ropes, it would evidently be true economy to use the more expensive rope.

In handling wire rope, it must not be coiled and uncoiled like hemp rope. When it is received from the manufacturers, wound on a reel, the latter should revolve on a spindle while the rope is paid off; when in a coil not on a reel, the coil should be rolled on the ground like a wheel, the rope being thus paid off so as to avoid any danger of untwisting or kinking.

It is also a cardinal point to make the driving-wheels as large as possible, as will appear later in considering the stresses on the rope.

Under no circumstances should galvanized rope be used for running-rope, as

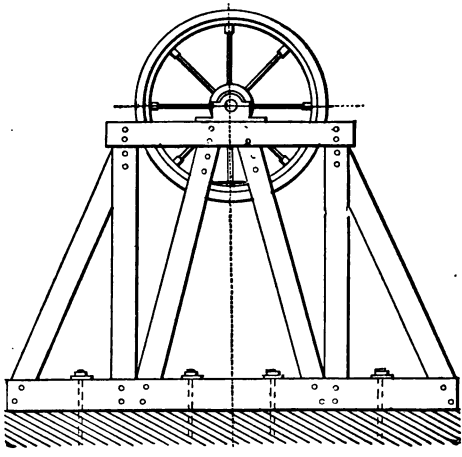
the coating quickly wears off, and rusting then proceeds with great rapidity. To preserve the rope, raw linseed oil or a mixture of the same with Spanish brown or lamp-black is to be preferred. A heated mixture of grease and resin is sometimes used with success, as are also many of the heavier lubricating compounds.

Supports for the Wheels.—The driving-wheels and their shafts are supported at the necessary height on strong wooden or masonry foundations, braced, if necessary, to resist the horizontal pull of the ropes. The length of the shaft between journals should not be less than the radius of the wheel. The only important feature about mounting the wheels is to get them absolutely vertical and to get all the wheels carrying the same rope in the *same* vertical plane. The efficiency and durability of the system will be much impaired by neglect of these points.

The supports themselves range in style and dimensions from the simple wooden frame shown in Fig. 11 and the iron one

of Fig. 12 to the more ornamental stone structure of Figs. 13 and 14, and thence to such large masses of masonry as are shown in Plates I and II.

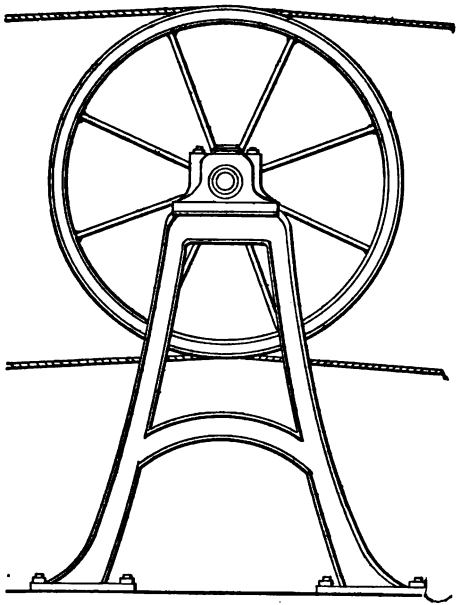
Fig. II.



Carrying Sheaves, Intermediate Stations, etc.—When the distance of transmission materially exceeds three or four hundred feet, or when there is not sufficient height available for the sag of the rope, the latter is usually supported at intermediate points by *carrying-sheaves.*

Sometimes it is sufficient to support only the following side of the rope, and generally, whatever the number of sheaves, the

Fig. 12.



driving side is supported at one less point than the following side. The same number of sheaves may, however, be used,

Fi . 13

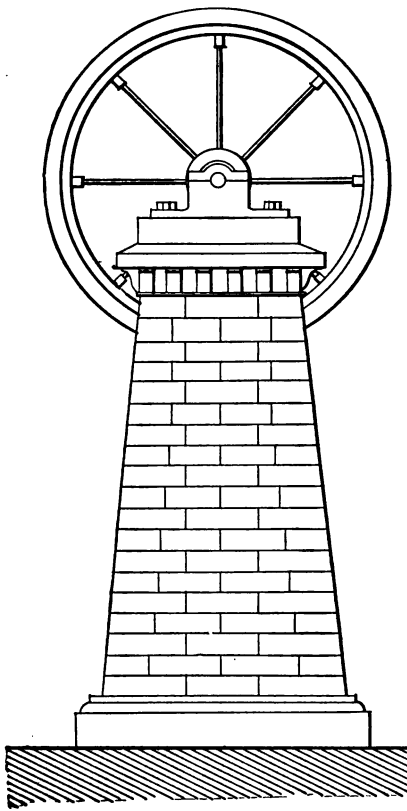
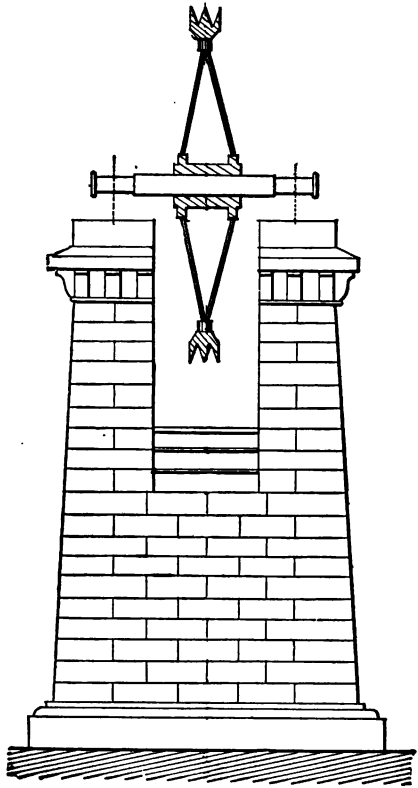


Fig. 14.



placing one over the other. The sheaves must never be placed side by side, as has been sometimes done to the great detriment of the transmission, the rope wearing out very rapidly against the side of the wheel-rim.

The sheaves supporting the driving side of the rope must in all cases be of equal diameter with the driving-wheels; and this for the same reason that the latter are usually made of so large a diameter. For whether the rope laps half way round on the driving-wheels, or only quarter way round on the carrying-sheaves, makes no difference—the tension due to bending is the same in both cases. With the following side, however, a somewhat smaller wheel may be used, owing to the fact that there is less direct tension on this side, and it is therefore better able to stand the additional tension due to bending.

The system of carrying-sheaves may generally be replaced with advantage by that of *intermediate stations*. When the latter is used, we have at each station, instead of two carrying-sheaves, one double-

egarde.

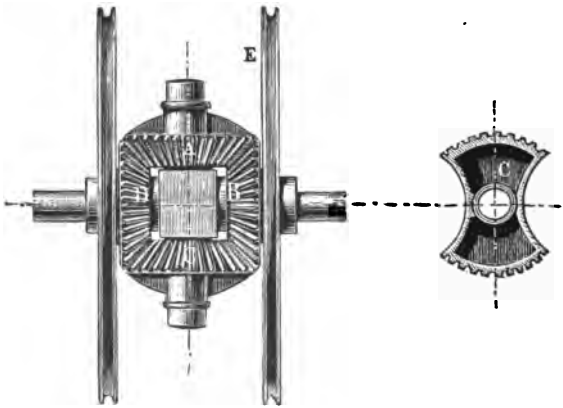
grooved wheel (see Fig. 14). The rope, instead of running the whole length of the transmission, runs only from one station to the other. It is advisable to make the stations equidistant, so that a rope may be kept on hand, ready spliced, to put on the wheels of any span should its rope give out.

For very powerful transmissions, it becomes advisable to employ two parallel ropes, either of which should be capable of transmitting the *entire* power. Even if the latter condition is not adhered to, it yet often happens that two parallel ropes are employed. In all such cases it is almost impossible to preserve equality between the tensions of the parallel ropes and between the diameters of their wheels. The best arrangement seems to be to have the two *driving*-wheels rigidly connected to the same shaft, but to let the two *following*-wheels run loose on their shafts, connecting them by a differential gear, such as shown in Fig. 15.

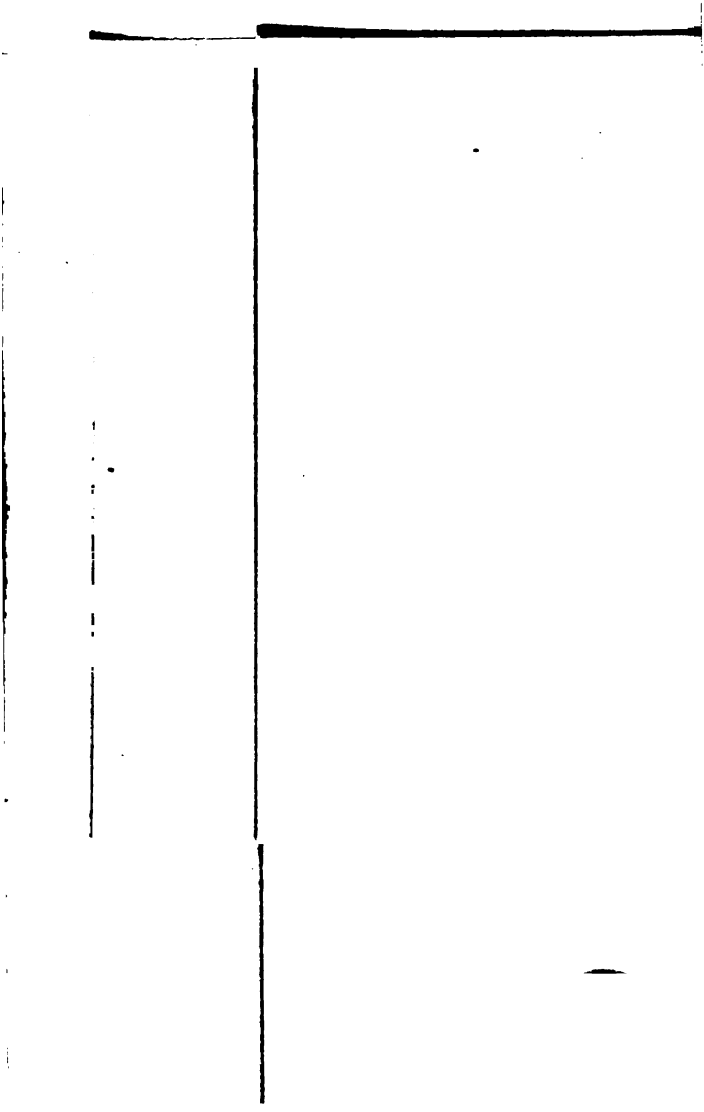
The rope-wheels are rigidly connected with the bevel wheels, *B* and *D* respectively, the latter being in gear with the

bevel wheels *A* and *C*. The axes of *A* and *C* are in the same straight line, and they are supported in a rigid frame firmly connected to the main shaft. The result is that, when the tensions of the

Fig. 15.



ropes are not the same, there is a slight additional rotation of one wheel or the other, causing the equalization of the tension. This produces slight vertical oscillations, which have, however, no prejudicial influence on the working of the ropes.

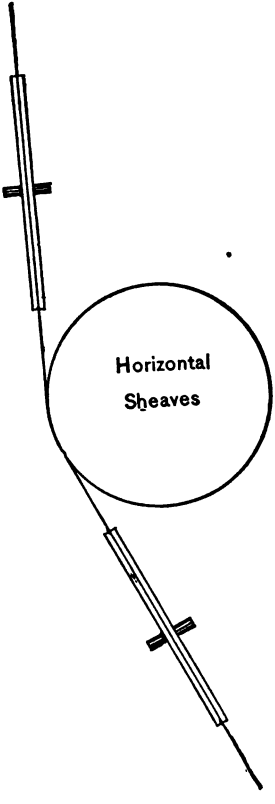


In case one of the ropes should break, the power transmitted on the other would no longer rotate the shaft, but would cause the violent rotation of the freed wheel. A brake is usually so connected with the apparatus as to stop the prime mover in such an event. To avoid any danger to the freed wheel from excessive speed of rotation, it has been proposed to form the gears *A* and *C* as sectors only, as shown to right of figure, in which case the freed wheel would be promptly thrown out of gear.

If it is required to change the direction of the rope at any point, it can be done by the interpolation of horizontal sheaves of same size as driving-wheels (Fig. 16).

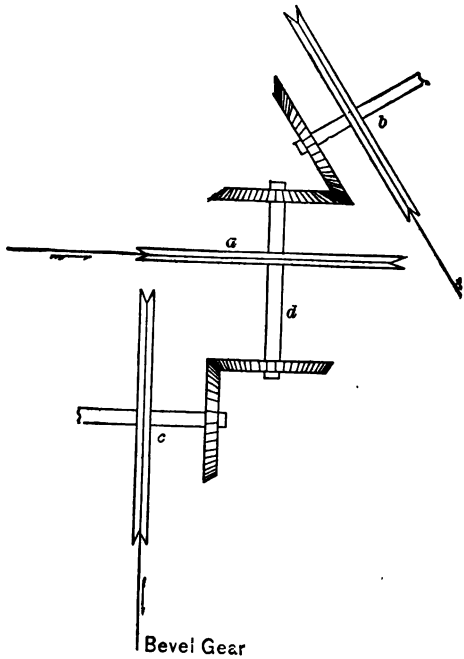
This method is not, however, to be recommended. It will usually be found much better to end the driving-rope over an ordinary vertical driving-wheel (*a*, Fig. 17), the shaft of which is connected by bevel gears with the shafts of similar wheels leading off new ropes at the desired angles. This arrangement is also usually adopted for a distributing

Fig. 16.



station, where the power brought thus far by a single rope or a pair of parallel

Fig. 17.



ropes is to be distributed to consumers in different directions.

Maintenance.*—In the transmission of power by wire ropes, the greatest attention must be paid to keeping the ropes and the lining of wheels in thorough repair. Even when they are exceedingly taut on the wheel at first, it has been found by experience that, after a short time, the ropes stretch considerably. This causes them, particularly in summer, to sag so much as to incapacitate them from transmitting the whole force, causing them to slip on the wheels; or they begin to drag on the ground or other obstructions. This evil may be partially remedied by shortening and again splicing the rope, which, however, should be avoided as long as possible, as the rope is injured more by several resplicings than by long running under the regular working tension. It is of course evident that a wire rope will stretch more as the wires make a greater angle with the axis of the rope; but as a rope having its wires parallel to the axis would be useless, we must keep

* See Ziegler's "Betrieb und Instandhaltung der Drahtseiltriebe" (Winterthür, 1871).

the angle at its minimum value, as dictated by practical experience.

Experiments made with a view to stretching the ropes before putting them into use have not been very successful. It is only lately that the problem has been partially solved by Mr. D. H. Ziegler's method of compressing the ropes while subjecting them at the same time to a great tensile strain. Wire ropes with wire centers, as sold in the market, are stretched in this manner from .22 to 1.2 per cent.

Wire ropes with hemp centers, as generally employed for the transmission of power, are stretched from .71 to 2.6 per cent. of their original length, without at all impairing their strength.

Although this is a great step in advance, reducing the stretching of the rope in use, with its accompanying disturbances, to a minimum, yet even this is not sufficient to maintain a constant tension and deflection in the rope, and we are often compelled to use other means to restore to the same its original tension.

The simplest and most effective way of attaining this end is by refilling the rims of the wheels, *i.e.*, by increasing their respective diameters to the proper amount, which is done in the following manner. Fig. 18 shows the cross-section of a wheel with leather filling, and Figs. 20 and 21 the same wheel with its diameter enlarged by the superposition of the new filling, which is best made of poplar or willow wood. It is made by taking straight pieces of about 1¼ inches in thickness, planing them into the necessary shape to fit the rim of the wheel, or merely cutting them into that shape by means of a circular saw, and providing their upper surfaces with grooves for the ropes. These pieces (Fig. 19) are made from four to six feet in length, and are provided on their insides with saw-cuts going half way through the wood. The pieces are first steeped in water for a day or two, to render them more flexible. They are then nailed to the leather filling by means of suitable wrought nails, which should be somewhat longer than the thickness of both

Fig. 18.

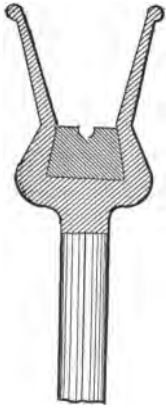


Fig. 19.

fillings together, so that after passing through the leather they may strike the iron below and be clinched, thus affording a better hold. The nails must be driven as shown, and especial care must

Fig. 20.

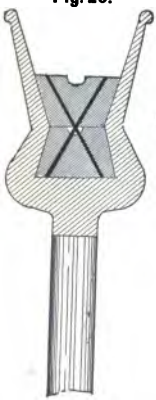
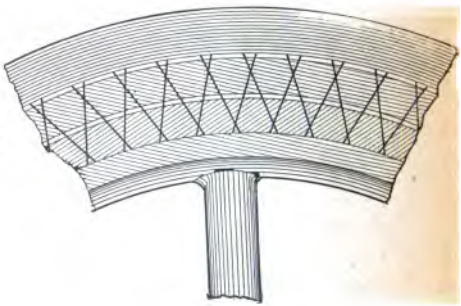


Fig. 21.



be taken that there are no projecting ends within reach of the rope. The whole operation can easily be performed in an hour, without throwing off the rope. In case the filling of one wheel in this manner is not sufficient to accom-

plish the desired result, the same operation is performed on the other wheel. If this is still insufficient, the whole process is repeated with a second layer. When the rope has finally become of a constant length, which usually takes place in the course of a few months, we may carefully remove all but the leather filling, and then shorten the rope to the proper length, allowing it to run on the original filling. After this treatment, there is usually no more trouble to be apprehended from this source.

When the transmission is in good running order, the ropes should run very steadily and without swaying laterally.

To ensure such results, a few principal points are to be specially looked after. In the first place, it is absolutely necessary to balance the wheels perfectly ; as, if they are not perfectly circular and well balanced, the centrifugal force, at the velocity with which they are driven, exercises a very prejudicial effect on the bearings of the shaft, as well as on the rope. The bearings wear out faster and more power is wasted in useless friction,

while the rope begins to swing, sometimes to such an extent as to be thrown violently against the side of the wheel-groove, thus wearing out very rapidly.

In mounting a transmission, the greatest care should be taken to get the wheels in the same vertical plane and the shafts perfectly horizontal, inasmuch as any deviation from this position immediately shows itself in the swaying of the rope, and, in addition, the latter rapidly wears out through friction on the wheel-rims.

In case the filling is in bad condition and worn unequally, it causes the rope to swing in a vertical plane. The remedy is to cut the filling so as to make it equally thick all around, or, in case the rope is also too slack, the filling may be increased in thickness, as already explained.

If there are ends of wires projecting from the rope, then every time that one of these projections passes over the wheel, the rope receives a slight shock, causing it to swing. The same action

takes place if torn or loose strands occur in the rope.

If the rope has been badly spliced or given a false turn or kink, it will not run steadily.

When the rope has stretched to such an extent as to touch the ground or other obstructions, it begins to swing violently. An attempt has sometimes been made to remedy this by putting in a little roller or guide, which, however, usually makes matters worse.

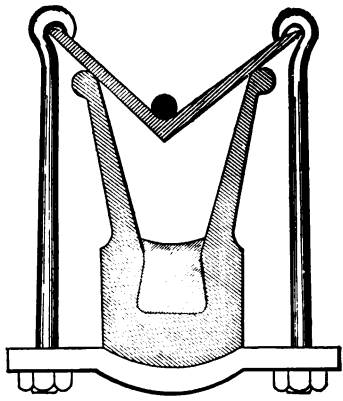
There are some other causes which induce an irregular action in the rope. For instance, if a wire rope is transmitting a constant power to a certain distance, and if the wheels, ropes, etc., are in good order, it will run steadily as long as the power transmitted corresponds to a certain tension and deflection in the rope. But now, if some of the machines are suddenly thrown in or out of gear, the tension in the rope and its corresponding deflection will be changed, thus causing the motor to adapt its speed to suit the altered demand for power, the rope at the same time sway-

ing gently in a vertical plane. This property is of great value, particularly in long transmissions, as it prevents sudden changes in velocity, the rope itself acting as a sort of governor.

Wire ropes are sometimes employed to transmit the power of a steam-engine to a distant building, or to combine its power with that of some hydraulic motor. In such cases, we must be careful to insure the regular action of the steam-engine; as it often happens, particularly in the case of an expanding, single-cylinder engine, with a light or badly balanced fly-wheel, that the speed during a stroke is very irregular. If we attempt to transmit the power of such an engine by means of wire ropes, the result will be a series of oscillations in the latter, in synchronism with the stroke of the engine. When this occurs, it can only be remedied by using a heavier and better balanced fly-wheel, or by adding a second cylinder to the engine. When a rope is used in connection with a steam-engine, the latter should be provided with a very powerful,

quick-acting governor, in order to prevent the overrunning of the engine if the rope should suddenly break. Such an accident happened some years ago in a cotton-spinning establishment in Alsace, causing the complete destruction of a large steam-engine.

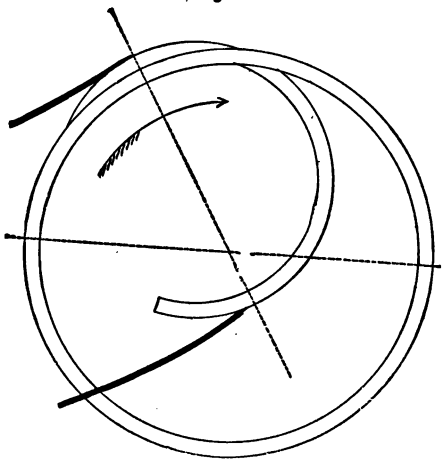
Fig. 22.



To facilitate the putting on of previously spliced ropes, the wheels are often overhung instead of having their shafts supported at both ends. In such cases, the application of the ropes to the

wheels is much facilitated by the simple device shown in Fig. 22. It consists simply of a few feet of angle iron, bent to a curve of about half or two thirds the diameter of the wheel, and having one

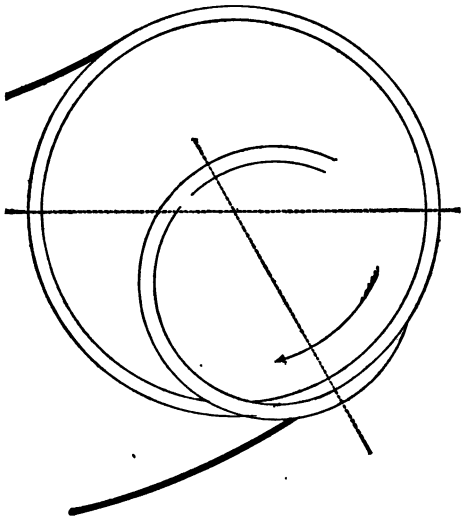
Fig. 23.



end lying in the groove of the wheels and held there by a couple of bolts. The wheel being in position shown in Fig. 23, the rope can easily be laid in the groove of the angle-iron leader; and giving the wheel half a revolution in the direction

of the arrow, brings the rope entirely into the wheel groove (Fig. 24). The angle iron leader is then taken off and the transmission is ready to go ahead.

Fig. 24.



In case the driving-rope crosses streets or other thoroughfares, it is essential to prevent obstruction to the latter or danger to passing persons or vehicles in case the rope should break. The simplest

means of accomplishing this result consists in stretching two fixed wire ropes across the thoroughfare, approximately parallel to and about one foot above and three or four feet on either side of the lowest position of the lower side of the transmission rope. These two fixed ropes are connected at every 9 or 10 feet by light round iron rods, curved down in the center to two or three feet below the line of the driving-rope. A sort of continuous net is thus formed, effectually preventing the loose ends from dragging on the ground in case of fracture. In such cases, any gradual stretching of the driving-rope must be remedied at intervals sufficiently frequent to prevent it from touching the cross-rods.

STRESSES IN THE ROPE.

THE principal stresses in a wire rope in motion are—

(1) Direct tension corresponding to the power transmitted, and due to the weight of the rope itself, and to the necessary stretching of the rope over the wheels to insure sufficient friction;

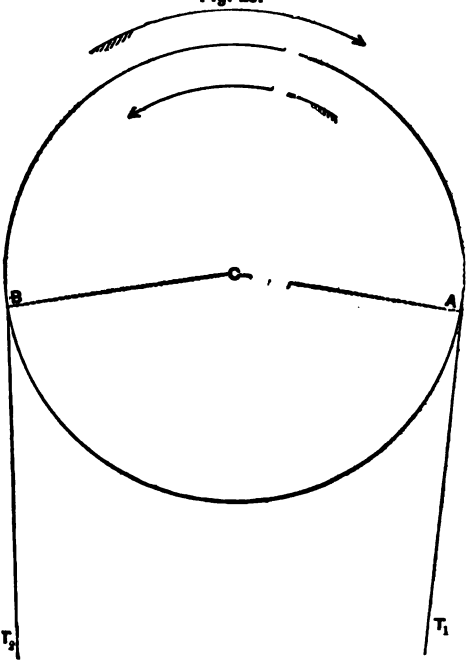
(2) Tension and compression in the portion of the rope at any time in contact with circumference of wheel, due to the bending of the wires;

(3) Tension due to the centrifugal tendency of the portion of the rope at any time in contact with circumference of wheel.

Direct Tension.—Taking up the consideration of the first of these stresses, let Fig. 25 represent a wheel about a portion of whose circumference is wrapped a perfectly flexible rope, the arc of contact being θ. The wheel and the rope

are supposed to tend to move in the directions of the inner and outer arrows

Fig. 25.



respectively, their motion being just barely prevented by their total mutual friction F due to the tension of the rope.

This friction for any length of arc is equal to the difference of tension at the two ends of the arc, and is also equal to the coefficient of friction between the rope and the wheel, multiplied by the normal pressure over that arc. Let f represent this coefficient of friction, let T represent the varying tension of the rope along the arc of contact with the wheel, and let T_1 and T_2 represent the tensions of the *driving* and *following* portions of the rope respectively.

Then for any elementary arc $d\,\theta$, the normal pressure over which is $T\,d\,\theta$, the friction will be

$$d\,F = d\,T = f\,T\,d\,\theta.$$

Integrating this expression over the whole arc of contact, θ, we get

$$\text{Nap. log. } \frac{T_1}{T_2} = f\,\theta, \text{ and } \frac{T_1}{T_2} = e^{f\,\theta},$$

(e being the base of the Naperian system of logarithms); so that the total friction, and hence the total pull that can be transmitted, is

$$F = T_1 - T_2 = T_2\,(e^{f\,\theta} - 1). \quad . \quad (1)$$

In a wire-rope transmission, the rope passes over two such wheels. If the wheels are of different sizes, or if the arc of contract is not the same on both wheels, this computation must be made for both wheels; and the power which can be transmitted is equal to the lesser of the two frictions so found. Ordinarily, the conditions at the two wheels are identical. If the wheels are allowed to come to rest, it is found that the tensions of the two free portions of the rope become the same, being equal to the mean of the tensions of the driving and following portions of the rope while in motion. The ratio which this mean tension bears to the force which can be transmitted when the wheels are in motion is

$$\frac{T_1 + T_2}{2F} = \frac{e^{f\theta} + 1}{2(e^{f\theta} - 1)} \quad \cdot \cdot \quad (2)$$

In wire-rope transmission, the rope is in contact with one half the circumference of each wheel, or $\theta = \pi$; and, for wire rope running on leather or hard rubber, $f = 0.25$. The value of $e^{f\theta}$ then be-

comes $e^{\frac{\pi}{4}} = 2.188$; and the previous equations become

$$\frac{T_1}{T_2} = 2.188; \quad \frac{T_1}{F} = 1.84; \quad \frac{T_1 + T_2}{2F} = 1.34.$$

In practice, it is usual to assume

$$\left.\begin{aligned} T_2 &= F \\ T_1 &= 2\,T_2 = 2\,F \\ \frac{T_1 + T_2}{2} &= 1.5\,F \end{aligned}\right\} \quad . \quad . \quad . \quad (3)$$

Hence, the transmission of the force F with the linear velocity of the wheel-rim causes a direct tension $T_1 = 2\,F$ on the driving side of the rope.

Let D = diameter of rope in inches,
d = diameter of wire in inches,
a = total cross-sectional area of wires,
t_1 = tension per square inch of wires (in driving side of rope) due to transmission of F.

Then $$T_1 = t_1 a = 2\,F$$

and $$a = \frac{2\,F}{t_1}.$$

In the wire rope (Fig. 5) commonly used for this purpose, there are 42 wires and $D = 9\,d$; hence $a = 42\,\frac{\pi\,d^2}{4} = \frac{42\,\pi\,D^2}{4 \times 81} = 0.4072\,D^2$. Substituting this value of a in the expression just found, and solving, we have

$$D^2 = 4.9116\,\frac{F}{t_1}. \quad . \quad . \quad (4)$$

Let H = number of horse-power to be transmitted,
R = radius of wheel in inches,
N = number of revolutions per minute.

Then $$F = \frac{33000\,H}{2\,\pi\,\frac{R}{12}\,N} = \frac{198000\,H}{\pi\,R\,N},$$

$$D^2 = \frac{4.9116 \times 198000\,H}{\pi\,R\,N\,t_1},$$

and $$D = 556.4\sqrt{\frac{H}{R\,N\,t_1}}. \quad . \quad . \quad . \quad (5)$$

To find the value of D from this equation, we must at the very outset know what is the *proper* tension t_1 to use in the ropes; and we must thus at once proceed

to determine the amount of the tensions due to bending and to centrifugal force, as these must be substracted from the *total* tension allowable in the rope to obtain the tension t_1 which is available for the actual transmission of power.

Bending Tension.—Passing to the consideration of the stresses caused by bending round the wheel (Fig. 26), let

R = radius of wheel in inches,
d = diameter of wire composing rope in inches,
E = modulus of elasticity of wire,
t_2 = tension per square inch of wires, caused by bending action.

When the rope is compelled to bend to the curve of the wheel, the outer fibres of each wire will be extended and the inner ones compressed, while the center (the neutral axis) will remain unchanged in length.

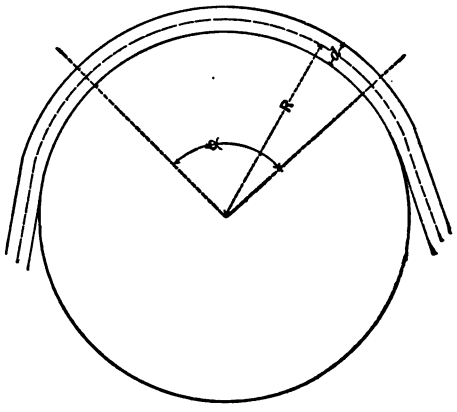
The length of the neutral axis of a wire subtending any angle α is $\lambda_1 = \frac{\pi}{180} R\ \alpha$.

The outermost fibre of this wire subtends

the same angle with radius $R + \frac{d}{2}$, its length being thus $\lambda_2 = \frac{\pi}{180}\left(R + \frac{d}{2}\right)\alpha$. The amount by which the outermost fibre has been extended is thus

$$\lambda_2 - \lambda_1 = \frac{\pi}{180} \cdot \frac{d}{2} \cdot \alpha;$$

Fig. 26.



and the extension per unit of original length is

$$\frac{\lambda_2 - \lambda_1}{\lambda_1} = \frac{d}{2R}.$$

Then, from the definition of the modulus of elasticity, we have

$$E = t_2 \div \frac{d}{2R} = \frac{2Rt_2}{d};$$

whence
$$t_2 = \frac{Ed}{2R}, \quad . \quad . \quad . \quad (6)$$

and
$$\frac{R}{d} = \frac{E}{2t_2} \quad . \quad . \quad . \quad . \quad (7)$$

From these equations the tension may be determined. For the elasticity of iron wire we may take the mean of various experiments, viz., 28,000,000 lbs. Substituting this value of E and also introducing for d its usual value $\frac{D}{9}$, we have for the tension per square inch caused by bending

$$t_2 = \frac{28000000\ D}{18\ R} \quad . \quad . \quad . \quad (8)$$

Substituting in equation (8) some of the probable values of the ratio $\frac{R}{D}$, we get the following table:

$\frac{R}{D}$	t_2	$\frac{R}{D}$	t_2
40	38888	120	12963
45	34570	130	11965
50	31111	140	11111
55	28282	150	10730
60	25925	160	9722
65	23930	170	9150
70	22222	180	8642
75	20740	190	8187
80	19444	200	7777
85	18300	210	7407
90	17284	220	7161
95	16374	230	6763
100	15555	240	6481
110	14141	250	6222

For steel wire the modulus of elasticity would be about 30,000,000, and the values of t_2 would be proportionately higher.

This table shows clearly the cause of the rapid wear of the ropes when running on small pulleys. When the ratio $\frac{R}{D}$ is large, the tension due to bending is small in comparison with the total allowable tension (see p. 81), and varies but slightly with small changes in this ratio; while, if the latter is small, the tension due to bending is not only a large proportion of

the total allowable tension, but in extreme cases is even greater than this tension.

On the one hand, as the ratio $\frac{R}{D}$ decreases, the wheels become smaller and less expensive; but on the other hand, we can get but little *useful* tension on the ropes, or if we increase the latter, the strain becomes so great that the ropes soon wear out.

Centrifugal Tension.—Taking up the consideration of the tension due to the centrifugal action of the rope, let

g = acceleration of gravity = 32.2 feet per second;

w = weight of the rope in pounds per running foot;

v = velocity of the rope in feet per second;

r = radius of wheel in feet;

t_s = tension per square inch of wires due to centrifugal force.

Then the centrifugal force is

$$p = \frac{m v^2}{r} = \frac{w}{g} \cdot \frac{v^2}{r},$$

and the total tension due to this centrifugal force is

$$p\,r = \frac{w\,v^2}{2\,g}.$$

In the 42-wired ropes in ordinary use $w = 1.5\ D^2$, and the total cross-sectional area of wires is $a = 0.4072\ D^2$.

Hence, for this rope, the *intensity* of this tension is

$$t_2 = \frac{w\,v^2}{2\,a\,g} = 0.1144\,v^2, \quad . \quad (9)$$

being thus independent of the diameter of the rope.

Substituting some of the probable values of v, we have

v	t_2	v	t_2
30	103	70	561
40	183	80	732
50	283	90	927
60	412	100	1144

Total Tension.—While any transmission is in operation, the rope is subjected to all three of the tensions previously considered. The actual and relative

amounts of these different tensions we may vary at pleasure, provided only that their sum ($K_0 = t_1 + t_2 + t_3$) does not exceed a certain amount, depending on the nature of the material of the wires.

This maximum allowable intensity of tension may be taken rather higher in wire rope than when the material is used in larger masses, as wire-drawing is itself a process of testing and selection, only high grades of iron being capable of being drawn into wire.

For iron wire rope it is safe and customary to take $K_0 = 25{,}600$ pounds per square inch of wires; while for the special grades of cast-steel ropes we may go as high as 50,000 pounds. It is, however, generally better in the case of steel ropes not to go very much above the usual limit for iron, and to employ the superior strength of the steel rope, not to transmit a greater force, but to enhance the durability of the rope.

In apportioning the total tension into its three components, we first estimate the speed at which the ropes are to run and deduct the tension, t_3, due to centri-

fugal force at that speed, from the whole tension, K_0. In all ordinary cases we need not for this purpose estimate the *exact* speed, but may assume $t_2 = 600$ pounds, so that we will then have for iron rope a tension $K = K_0 - 600 = 25{,}000$ pounds per square inch to divide between t_1 and t_2.

The principal conditions determining the best relative values of t_1 and t_2 are two in number—(1) the size of wheel that may be conveniently employed, (2) the resulting deflection or sag in the ropes; the latter being again subject to various conditions, such as the available height, distance between wheels, etc.

Combining equations (5) and (7) we get

$$R^3 = \frac{30955\, E^2 H}{324\, N} \cdot \frac{1}{t_1 t_2^2}.$$

The condition under which the value of R is a minimum is obtained by placing the first differential coefficient of this equation equal to zero, which gives

$$t_2 = 2\, t_1; \quad . \quad . \quad . \quad (10)$$

in other words, in the case most favorable to small wheels the tension caused by bending is twice as great as the direct tensional strain, and is hence, of course, $t_2 = \frac{2}{3} K$ where $K = 25{,}000$.

As a rule, it is advisable to use a wheel considerably larger than would be given under such conditions, and the best practice seems to indicate, as most suitable, a value $t_1 = t_2 = 12{,}500$, which corresponds to about $R = 125$. Making proper substitutions in equation (5) we have

$$D = 0.583 \sqrt[3]{\frac{H}{N}}, \quad . \quad . \quad (11)$$

and the *diameter* of the corresponding wheel in *inches* is

$$d = 2R = 146 \sqrt[3]{\frac{H}{N}}. \quad . \quad . \quad (12)$$

The diameter of wheel given by equation (12) agrees fairly well with that used in practice; but the ropes are usually made from $\frac{1}{8}$ to $\frac{1}{4}$ inch larger in diameter than given by equation (11), both for the sake of enhancing the durability of the rope, as well as to counterbalance the effect of stretching by giving the rope an

initial tension greater than the normal working tension.

We now pass to the consideration of the causes directly producing the tension t_1, and the manner of fixing its proper amount in any actual case.

The Catenary.—If a perfectly flexible rope be secured at two points and loaded continuously between them according to any law, it will assume some definite curvilinear form. When the load is the weight of the rope only, the curve is called a *catenary*.

Suppose that the rope is fixed at the points A and B (Fig. 27), and that the only force in operation is the weight of the rope, *i.e.*, the load is a continuous and direct function of the length of arc. Take the origin of co-ordinates at C, the lowest point of the curve, and let the axes of x and y be horizontal and vertical respectively.

Let t_1 = tension at any point a;
t_0 = tension at origin C;

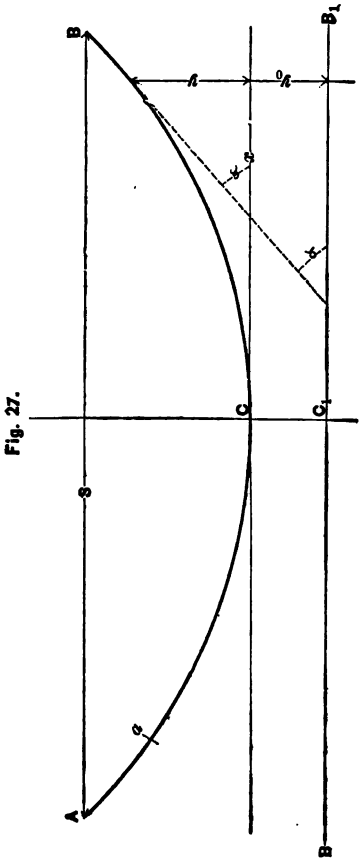


Fig. 27.

l = length of curve $a\ C$;
L = total length of curve between supports $A\ B$;
w = weight of rope in pounds per running foot;
S = span between supports;
Δ = total deflection or greatest ordinate of curve.

Then the point a is kept in equilibrium by the tension t' and the applied forces between C and a. These applied forces are the tension t_0 acting horizontally at C, and the weight of the rope, $w\,l$, acting vertically along $a\ C$.

Resolving vertically and horizontally, we have as the equations of equilibrium,

$$t' \frac{dx}{dl} = t_0 \quad . \quad . \quad . \quad (13)$$

$$t' \frac{dy}{dl} = w\,l. \quad . \quad . \quad (14)$$

Thus the horizontal component of the tension at any point a is equal to the tension at the lowest point, *i.e.*, the horizontal component of the tension is constant throughout the curve; and the vertical component of the tension at any point is

equal to the weight of so much of the rope as comes between the origin and the point considered.

Dividing equation (14) by equation (13), we get, for the tangent of the angle which the rope at any point a makes with the horizontal,

$$\tan \alpha = \frac{dy}{dx} = \frac{wl}{t_0}. \quad . \quad . \quad (15)$$

Differentiating equation (15), we have

$$d\left(\frac{dy}{dx}\right) = \frac{w}{t_1} dl;$$

but $dl = (dx^2 + dy^2)^{\frac{1}{2}} = \left(1 + \frac{dy^2}{dx^2}\right)^{\frac{1}{2}} dx.$

Substituting this value, we have, after transposing,

$$\frac{w}{t_0} dx = \frac{d\left(\frac{dy}{dx}\right)}{\left(1 + \frac{dy^2}{dx^2}\right)^{\frac{1}{2}}}. \quad . \quad (16)$$

Integrating equation (16) we obtain

$$\frac{w}{t_0} x = \text{Nap. log.} \left(\frac{dy}{dx} + \sqrt{1 + \frac{dy^2}{dx^2}}\right),$$

which may be written

$$e^{\frac{wx}{t_0}} = \frac{dy}{dx} + \sqrt{1 + \frac{dy^2}{dx^2}}, \quad . \quad (17)$$

where e is the base of the Naperian system of logarithms.

Transposing, squaring, and simplifying equation (17), we get

$$dy = \tfrac{1}{2}\left\{ e^{\frac{wx}{t_0}} - e^{\frac{-wx}{t_0}} \right\} dx. \quad (18)$$

Integrating the above equation between any point (x, y) and the origin, we have

$$y + \frac{t_0}{w} = \frac{t_0}{2w}\left\{ e^{\frac{wx}{t_0}} + e^{\frac{-wx}{t_0}} \right\}, \quad . \quad (19)$$

which is the equation of the catenary. To bring this equation into a somewhat simpler form, we transfer the origin of co-ordinates to C_1, making $C C_1 = \frac{t_0}{w}$. This line $C C_1$ is called the *parameter* of the curve. Then our new ordinates will be $y_0 = y + \frac{t_0}{w}$; so that equation (19) may be written

$$y_0 = \frac{t_0}{2w}\left\{ e^{\frac{wx}{t_0}} + e^{\frac{-wx}{t_0}} \right\}. \quad (20)$$

But this change of origin evidently does not affect the value of $\frac{dy}{dx}$, the tangent of the angle α; and substituting $\frac{dy}{dx} = \frac{wl}{t_0}$ from equation (15) in equation (18) we obtain, for the length of arc,

$$l = \frac{t_0}{2w}\left\{ e^{\frac{wx}{t_0}} - e^{\frac{-wx}{t_0}} \right\}. \quad . \quad (21)$$

Subtracting the square of equation (21) from the square of equation (20), we have

$$y_0^2 - l^2 = \frac{t_0^2}{w^2};$$

$$l = \sqrt{y_0^2 - \frac{t_0^2}{w^2}}; \quad . \quad . \quad (22)$$

and the whole length of the rope between supports, for which $y_0 = \Delta + \frac{t_0}{w}$, is

$$L = 2\sqrt{\Delta^2 + \frac{2\Delta t_0}{w}}. \quad . \quad (23)$$

This equation gives the means of computing the length of the rope when, in addition to the deflection, the running weight of the rope and the ratio $\frac{t_0}{w}$ are

has its least value at the lowest point, where

$$t'_{min} = t_0 ; \quad . \quad . \quad . \quad (26)$$

and it reaches its maximum value at the points of support, where

$$t'_{max} = w \Delta + t_0, \quad . \quad . \quad (27)$$

being thus equal to the tension at the lowest point, plus the weight of a piece of rope whose length is equal to the deflection. The smaller the deflection of the rope, the less is the difference between t'_{max} and t_0. When $\Delta = 0$, we have $t' = t_0 =$ infinity, showing the impossibility of stretching a rope so as to be perfectly horizontal. The vertical component of the tension at each of the points of support is of course equal to the weight of one half the rope. That is,

$$t' \frac{dy}{dl}\Big]_{max} = \frac{wL}{2} = w\sqrt{\Delta^2 + \frac{2\Delta t_0}{w}}, \quad (28)$$

the horizontal component of the tension at the point of support being t_0, as already determined.

The angle which the curve at the point

known. The value of w is always known in any particular case, and for the 42-wired rope usually employed $w = 1.5\,D^2$.

The value of the ratio $\frac{t_0}{w}$, as obtained by solving equation (20), for either point of support, is

$$\frac{t_0}{w} = \frac{2\,\Delta}{e^{\frac{w\,S}{2\,t_0}} + e^{\frac{-w\,S}{2\,t_0}} - 2} \quad . \quad . \quad (24)$$

Its value depends thus directly on the relation between the deflection and span, being very large where $\frac{\Delta}{S}$ is small, as it always is in the transmission of power by wire rope.

For the tension *along* the rope at any point, we have

$$t' = \sqrt{\left(t'\frac{d\,y}{d\,l}\right)^2 + \left(t'\frac{d\,x}{d\,l}\right)^2}$$

$$= \sqrt{w^2\,l^2 + t_0^2}$$

$$= w\,y_0, \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (25)$$

being thus directly proportional to the weight of the rope per running foot. It

of support makes with the horizontal is given by

$$\tan \alpha]_{max} = \frac{w L}{2 t_0} = \frac{w}{t_0}\sqrt{\Delta^2 + \frac{2 \Delta t_0}{w}}. \quad (29)$$

Approximate Equations of Catenary.— In practically applying the preceding equations, we meet with considerable difficulty, owing to the fact that the parameter $\frac{t_0}{w}$ can only be obtained from a transcendental equation.

But in such work as forms the subject of this volume, we can pursue a frequently used method of approximation, which is abundantly accurate for all our purposes. The exact equations of the catenary, as we have deduced them, are of course applicable; but as we have left the stiffness of the rope out of consideration, and assumed it to be *perfectly flexible*, the properties of the curve are not expressed with mathematical exactness by even these equations. For this reason alone, it might be permissible to use approximate formulæ; but we have a still greater right to use them, because the

deflection Δ is always a very small fraction of the span S, and therefore the parameter $\frac{t_0}{w}$ is always very large.

Consequently, in equation (24) the exponents of e are small fractions, and we may express their values by the converging series

$$e^{\frac{wS}{2t_0}} = 1 + \frac{wS}{2t_0} + \frac{w^2S^2}{2\times 4t_0^2} + \frac{w^3S^3}{2\times 3\times 8t_0^3} +$$

$$e^{-\frac{wS}{2t_0}} = 1 - \frac{wS}{2t_0} + \frac{w^2S^2}{2\times 4t_0^2} - \frac{w^3S^3}{2\times 3\times 8t_0^3} +$$

Taking the first four terms of these series, and substituting them in equation (24), we get

$$\frac{t_0}{w} = \frac{2\Delta}{\frac{w^2S^2}{4t_0^2}} = \frac{S^2}{8\Delta}. \quad . \quad . \quad (30)$$

A similar modification of equation (20) gives

$$y_0 = \frac{t_0}{2w}\left(2 + \frac{w^2x^2}{2t_0^2}\right) = \frac{t_0}{w} + \frac{wx^2}{4t_0};$$

hence

$$y_0 - \frac{S^2}{8\Delta} = \frac{w x^2}{4 t_0}. \quad . \quad . \quad . \quad . \quad . \quad (31)$$

This is the equation of a parabola having a parameter of $\frac{S^2}{4\Delta}$; so that our method of approximation has led us to consider the curve as a parabola.

Making these substitutions throughout, the previously deduced exact formulæ now become

$$t'_{max} = w\left(\Delta + \frac{S^2}{8\Delta}\right). \quad . \quad (32)$$

$$t_0 = \frac{w S^2}{8\Delta}. \quad . \quad . \quad . \quad . \quad . \quad (33)$$

$$t' \frac{dy}{dl}\Big]_{max} = w\sqrt{\Delta^2 + \frac{S^2}{4}}. \quad . \quad (34)$$

$$\tan \alpha]_{max} = \frac{8\Delta}{S^2}\sqrt{\Delta^2 + \frac{S^2}{4}}. \quad . \quad (35)$$

$$L = 2\sqrt{\Delta^2 + \frac{S^2}{4}}. \quad . \quad (36)$$

Equation (36) is equivalent to assuming that the length of the curve between

either point of support and the lowest point is equal to the straight line joining those points. In using this equation, it must further be noted that the length of the actual rope after splicing must be $2L \times \pi R$, when Δ is the deflection *at rest.*

Practical Deductions.—It must be remembered that t'_{max} is not the maximum tension per square inch of wires, but the total maximum tension on the rope, being in fact the same as the tension T_1 or T_2, previously considered, for the driving and following sides respectively. Making our usual assumptions as to weight of rope per running foot, and relative diameters of wire and of rope, we find that for the common 42-wired rope the maximum tension per square inch is

$$t = \frac{t'_{max}}{a} = \frac{w}{a}\left(\Delta + \frac{S^2}{8\Delta}\right)$$

$$= 3.684\left(\Delta + \frac{S^2}{8\Delta}\right), \quad . \quad . \quad (37)$$

being thus independent of the diameter of the rope. For *different* varieties of

rope, the numerical constant would of course vary somewhat, and can be readily obtained for any case.

As we have previously seen, this tension is different in the driving and following portions of the rope while the latter is in motion, and has the same intermediate value in both sides of the rope while at rest.

A convenient way of practically ascertaining the tension of the rope at any time is by means of a vertical staff set in the ground near the lowest point of the rope. The staff being graduated by the formulæ found for the relation between tension and deflection, the tension can at any time be read off by simply sighting across the rope to the graduations on the staff.

In order that the rope may be subjected to its proper tension while in motion, the deflection or sag must be of a certain magnitude while the rope is at rest; we must also know the sag of the driving and following sides while in motion, in order to estimate the necessary elevation of the wheels. There are there-

fore three deflections to be determined: Δ_1, that of the driving side in motion; Δ_2, that of the following side in motion; Δ_0, that of both sides at rest.

We must know the deflection at rest, Δ_0, in order to determine the proper length of rope; so that when it is put on and spliced, we may feel certain that there will be neither any slipping during the motion, nor any over-straining of the rope itself. The deflections Δ_1 and Δ_2 must be known, in order to determine in advance what position the ropes will take while in motion, how near they will approach the ground or other obstructions, and how many, if any, carrying-sheaves are required.

Solving equation (37) for Δ, we get, for the value of the deflection,

$$\Delta = 0.1357\left(t - \sqrt{t^2 - 6.785\,S^2}\right). \quad (38)$$

The deflection of the *driving* side will be the least, and is

$$\Delta_1 = 0.1357\left(t_1 - \sqrt{t_1^2 - 6.785\,S^2}\right). \quad (39)$$

where t_1 is, as usual, the tension per square inch of wires (in driving side of rope) due to the transmission of F.

The deflection of the *following* side and the deflection *at rest* are similarly found by substituting in equation (38) the values $t = \frac{1}{2} t_1$ and $t = \frac{8}{4} t_1$ respectively. Thus we have

$$\Delta_2 = .0679 \left(t_1 - \sqrt{t_1^2 - 27.15\, S^2}\right); \quad (40)$$

$$\Delta_0 = .1018 \left(t_1 - \sqrt{t_1^2 - 12.06\, S^2}\right). \quad (41)$$

In all ordinary cases, where the following portion of the rope is below, the deflection of this side is the most important, as the necessary height of the wheels is thereby determined. This height must be so adjusted that the lowest portion of the rope will never touch the ground. Hence, assuming the ground to be level, the height of the center of the wheels above the ground must be at least $R + \Delta_2$, and should in practice be made somewhat greater to allow for the stretching of the rope. If the ground is

not level, or if there are obstructions, this height must be varied accordingly.

To give a better idea of the relative magnitude of the quantities involved, I have computed, by means of equations (37) and (38), the following tables, which will also be found useful as a first approximation in designing:

TENSION

PER SQUARE INCH OF WIRES FOR VARIOUS SPANS AND DEFLECTIONS.

Deflection in feet,	SPAN IN FEET.				
	100	200	300	400	500
¼	18,420	73,680	165,800	294,720	460,600
½	9,210	36,820	82,900	147,360	230,300
¾	6,140	24,570	55,250	98,250	153,500
1	4,610	18,420	41,450	73,680	115,150
2	2,310	9,220	20,730	36,850	57,580
3	1,550	6,150	13,830	24,570	38,390
4	1,165	4,620	10,380	18,430	28,800
5	940	3,700	8,310	14,750	23,050
6	790	3,090	6,930	12,300	19,210
7	685	2,650	5,950	10,550	16,470
8	605	2,390	5,210	9,240	14,420
9	545	2,080	4,640	8,220	12,826
10	495	1,880	4,180	7,400	11 550
12	465	1,580	3,678	6,223	9,640
15	362	1,283	2,818	4,966	7,732
20	304	995	2,146	3,758	5,832
25	276	829	1,750	3,040	4,697

DEFLECTIONS,

IN FEET, CORRESPONDING TO VARIOUS TENSIONS AND SPANS.

Tension, per square inch of Wires.	SPAN IN FEET.				
	100	200	300	400	500
25,000	.19	.72	1.66	2.99	3.26
20,000	.23	.92	2.08	3.68	5.77
17.500	.27	1.06	2.43	4 21	6.51
15,000	.32	1.24	2.77	4.94	7.68
12.500	.38	1.48	3.31	5 88	9 23
10.000	.46	1.84	4.21	7.40	11.56
7.500	.61	2.46	5.53	9.85	15.44
5,000	.92	3.69	8.35	16.26	23.42
4,000	1.15	4.63	10.46	18.74	29.57
3.000	1.53	6 20	14.03	25.34	40.35
2,000	2.31	9 36	21.58	39.74	65.40
1,000	4.68	19.89	51.04		
750	5.97	28.57			
500	9.94				

The blank spaces in this table indicate that the respective combinations are impossible. There is, in fact, for each span a certain deflection at which the tension has its minimum value ; so that any further increase of deflection beyond this point cause the tension again to increase, until finally both reach infinity together. Though this minimum tension and its corresponding deflection are entirely out of the range of ordinary practice, it will

nevertheless be of interest to determine their values. Differentiating equation (37) we have

$$\frac{dt}{d\Delta} = 3.684 \left(1 - \frac{S^2}{8\Delta^2}\right),$$

which being placed equal to zero, gives

$$\Delta = 0.3536\, S$$

as the deflection corresponding to the minimum tension, the value of the latter being

$$t_{min.} = 2.605\, S.$$

For the spans of the foregoing tables, we obtain the following values:

Span in Feet.	Minimum Tension per Square Inch of Wires.	Corresponding Deflection in Feet.
100	260	35 36
200	520	70.72
300	780	106.08
400	1040	141.44
500	1300	176.80

Examples.—Suppose for instance that it is required to transmit 300 horse-power over a distance of 200 feet, and that we are to put our first wheel on the main shaft of a steam-engine making 100 revolutions per minute. Equations (11)

and (12) would give us $D = 0.84$ and $2R = 210$, so that we should employ a $\frac{7}{8}''$ rope over a wheel $17\frac{1}{2}$ feet diameter. In all probability this wheel would be larger than would be convenient; in which case it would be advisable to use two ropes running side by side and each transmitting one half the power. For such an arrangement, we would find

$$D = .67 \text{ and } 2R = 168,$$

so that we should employ two $\frac{11}{16}''$ ropes running over 14-foot wheels.

The force to be transmitted by each rope would be $\frac{33000 \times 150}{\pi \times 14 \times 100} = 1125$ pounds; and the area of the wires in the rope is $0.4072\ D^2 = 0.192$ sq. inch. Hence, while at rest, the tension per square inch in both sides of the rope will be $\frac{1.5 \times 1125}{.192} = 8796$ pounds; while in motion, the tension on the *driving* side will be $\frac{2 \times 1125}{.192} = 11728$ pounds, and on the *following* side $\frac{1125}{.192} = 5864$ pounds.

Interpolating in table on p. 100, we find the deflection of both sides of the rope at rest to be about $25\frac{1}{2}$ inches; while in motion, the deflections of the driving and following sides will be about 19 and 39 inches respectively.

If greater exactness is required, the deflections may readily be calculated by means of the formulæ previously given. Allowance must always be made for the stretch of the rope, which increases the necessary height of wheels above ground.

The necessary length of rope after splicing is found by means of equation (36) and is

$$2L + 2\pi R = 4\sqrt{\Delta_0^2 + \frac{S^2}{4}} + 44$$
$$= 444 \text{ feet.}$$

If the rope, as above calculated, be just large enough to transmit the required power at the given deflection, it will no longer do so after stretching, on account of the decrease in tension accompanying the increased deflection due to stretching. This can only be avoided by re-splicing the rope as soon as the in-

creased deflection becomes perceptible, by refilling the wheel as previously explained, or, still better, by using a rope somewhat larger in diameter than found from eq. (11), giving to it a deflection corresponding to a greater tension than we need, thus allowing a margin for the decrease of tension accompanying increased deflection.

To illustrate, let it be required to transmit 50 horse-power at 80 revolutions. Equations (11) and (12) would give

$$D = 0.498 \text{ and } R = 124.8.$$

Taking an 11-foot wheel as the nearest larger wheel in the market, we would find the force to be transmitted to be $\frac{33000 \times 50}{\pi \times 11 \times 80} = 469$ pounds. If we were to use a $\frac{1}{2}$-inch rope, as given by equation (11), we should have tension per square inch of both sides at rest 6900, tension on following side 4600, and on driving side 9200 pounds. Supposing the distance of transmission to be 300 feet, the greatest deflection of the driving side, when just able to transmit the

force, would be about 4.6 feet. But as $\frac{R}{D} = 130$, we should have $t_2 = 11965$ and the maximum allowable value of $t_1 = 25000 - 11965 = 13035$, so that we could start work with a deflection of only 3.2 feet; and the power would be transmitted until the stretch had caused the deflection to exceed 4.6 feet.

We might do still better by employing a $\frac{5}{8}''$ rope, in which the tension per square inch on the driving side would only be 7256 pounds, corresponding to a deflection of about 5.8 feet. In this case $\frac{R}{D} = 114$, corresponding to $t_2 =$ about 13600. We should thus have a maximum value of $t_1 = 25000 - 13600 = 11400$, corresponding to a deflection of about 3.7 feet; so that the transmission would work satisfactorily while the deflection of the driving side underwent a variation of over two feet.

Similarly, in the first example above given, we have $\frac{R}{D} = \frac{84 \times 16}{11} = 122$, corresponding to about $t_2 = 12750$, and the

maximum value of $t_1 = 25000 - 12750 = 12250$, so that we could start with a deflection for the driving side of 18 inches, giving us 1 inch deflection to spare for stretching. A similar advantage would result in this case from the use of the next larger size of rope.

The relative and absolute sizes of wheels and ropes in any actual case may of course be considerably varied according to the designer's judgment, the only absolute condition being that $t_1 + t_2$ shall not, for iron ropes, exceed 25000 pounds. As a safe general rule, it may also be stated that the wheel should always be made as large as convenient.

The practice of one of the representative American firms is shown by their table on the following page.

As will be evident by computing any of the cases given in the table, a liberal margin has been allowed for any temporary increase of work or diminution of tension by increased deflection, and for the wear of the ropes.

Diameter of Wheels in feet.	Diameter of Rope in inches.	Horse-power Transmitted at—			
		80 Revs.	100 Revs.	120 Revs.	140 Revs.
3	½	3	3¼	4	4½
4	½	4	5	6	7
5	7/16	9	11	13	15
6	½	14	17	20	23
7	9/16	20	25	30	35
8	½	26	32	39	45
9	9/16	47	58	69	82
9	½	48	60	73	84
10	½	64	80	96	112
10	9/16	68	85	102	119
12	9/16	93	116	140	....
12	½	99	124	149	....
12	⅝	.....	.....	173	....
14	1	141	176	....	....
14	1¼	148	185	....	...

Special Cases.—The lower side of the rope is nearly always the *following* side; but if there is any difficulty about securing the necessary height to provide for the deflection of the following side while in motion, we may make the lower side the *driving* side, in which case the deflection at rest is the greatest to be provided for.

When in motion (fig. 28) the lower driving side rises above its position at rest, and the upper side sinks, thus enabling us to avoid obstructions, which

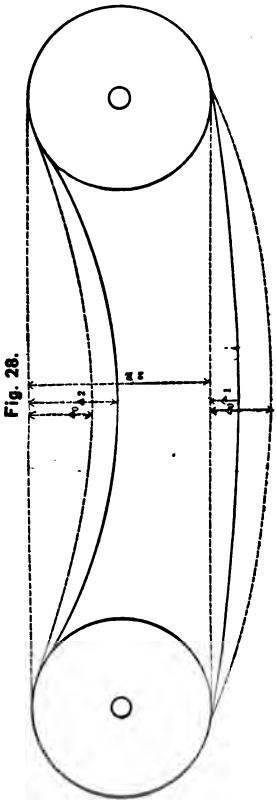


Fig. 28.

by the other way would have to be removed. Of course this expedient cannot always be employed, as the upper side of the rope must not be allowed to sink so far as to pass below or even to touch the lower side. If this occurs, the rope begins to sway and jerk in a serious manner, wearing out very rapidly.

The shortest distance between the ropes is $2\ R - (\Delta_2 - \Delta_1)$. We must therefore always be careful, in using this plan, to see that $2\ R > \Delta_2 - \Delta_1$, which result may be obtained by a judicious selection of the tension, and of the diameter of wheel.

The spans which may be used in practice are limited in one direction by the steadily increasing tension and deflection, and in the other by our inability to secure the necessary tension without special tightening devices.

The maximum limit has been already considered, and depends on local circumstances, being usually from 300 to 500 feet. The minimum limit may readily be obtained from equation (33), assuming that the deflection shall never be less

than 18 inches, and that t_0 shall never exceed 500 w. We then have

$$S = \sqrt{8 \Delta \frac{t_0}{w}} = 78 \text{ feet.}$$

Below this distance, shafting will usually be found preferable and less troublesome.

It sometimes happens that the two wheels are not at the same height, as has been hitherto supposed, but that one is at a higher level than the other. This frequently happens where it is desired to use the power of waterfalls in a ravine, or in conducting power up or down the side of a hill, the rope taking a position such as is shown in Fig. 29.

If the difference in height is slight, we can use the formulæ already found, without introducing any serious error. If the rise be considerable, however, the tension of the rope at the upper wheel will be greater than that at the lower. In this case, the power which can be transmitted depends only on the tension at the lower wheel, which may, if desired, be made smaller than the upper wheel, so

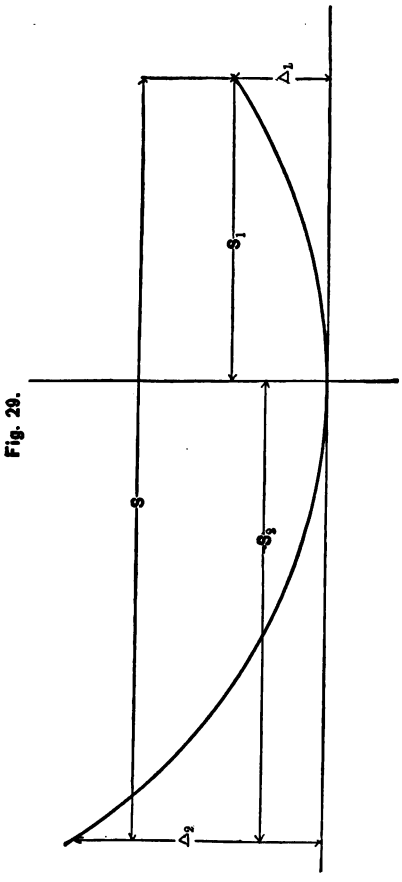


Fig. 29.

that the *total* tension in the rope in going round each wheel shall be the same. The total span being S, and the difference in level of the two ends A, then, by the known properties of the parabola, we have, for any deflections Δ_1 and Δ_2 (see Fig. 29),

$$S_1 = S \frac{\sqrt{\Delta_1}}{\sqrt{\Delta_1} + \sqrt{\Delta_2}}$$

$$= S \frac{\sqrt{\Delta_1}}{\sqrt{\Delta_1} + \sqrt{A + \Delta_1}}.$$

Assuming any convenient value of Δ_1, we make all the calculations for the lower wheel as though the span were $2\ S_1$, and for the upper wheel as though the span were $2\ S_2$. If the results are not satisfactory the first time, a few successive alterations of Δ_1 will readily give the desired results.

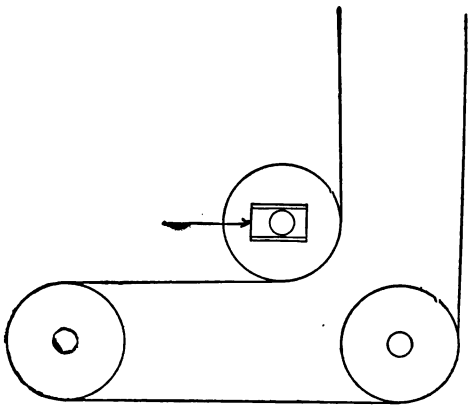
The readiest and most usually employed method of getting the value of S_1 is the following: An accurate scale-drawing is made of the plan in which the rope is to be placed. This drawing is set vertically, and a fine chain is fas-

tened or held with its two ends at the points of support until a proper deflection is obtained. It then becomes a matter of ease to measure S_1 and S_2, and to make all the necessary calculations. We can in this way try different deflections and observe their suitability to the design, but must always bear in mind whether we are getting the deflection of the driving or of the following side or that of both sides at rest. This method, though not giving as great accuracy as the solution of the above equation, is nevertheless largely used in practice, owing to its great convenience. It may be used when the pulleys are on the same level, showing between what limits we may work.

Another peculiar case is when the rope rises nearly in a vertical direction. This is the limiting case of the inclined transmission. The rope produces no tension whatever on the lower wheel, while at the upper wheel the tension is only equal to the weight of the rope. Even this last tension is such a small quantity as to be left entirely out of consideration, and we are consequently obliged to

use some device for producing the requisite tension, such as the tightening-sheaves shown in Figs. 30 and 31. In the latter, the rope passes around the wheel twice, so that the wheel must be provided with two grooves.

Fig. 30.

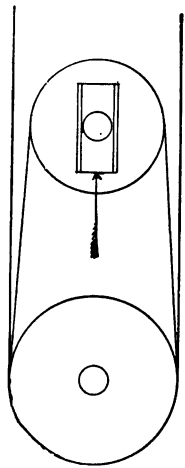


The requisite tension in the vertical ropes may also be obtained as shown in Fig. 32, by running them over two carrying-sheaves at the upper point and introducing a sufficient horizontal span

the deflection of which corresponds to the tension desired.

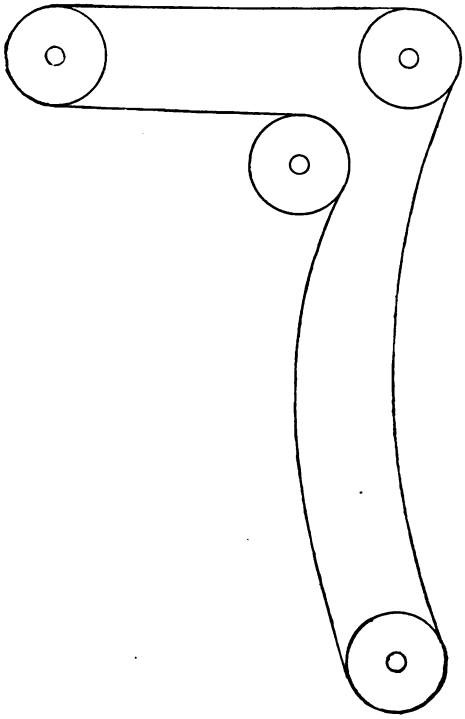
Pressure on Bearing.—A simple graphic method of finding the pressure on

Fig. 31.



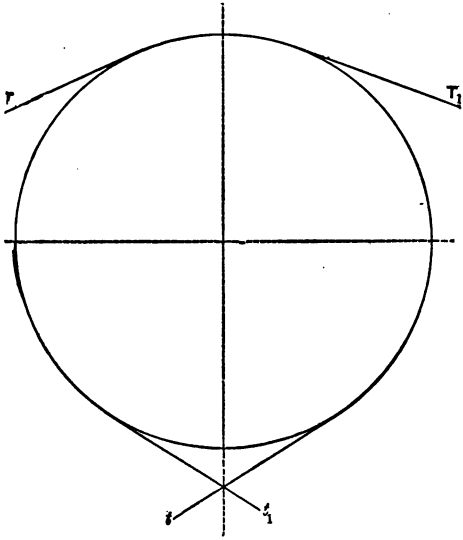
the wheel-bearings, and hence also the direction of the thrust on the supports, is shown in Figs. 33 and 34. Let Fig. 33 show the tensions on the ropes on a

Fig. 32.



double-grooved wheel at an intermediate station. Draw (Fig. 34) $A\,B$, $B\,C$, $D\,C$, $D\,E$ respectively parallel to, and on some convenient scale proportional to, T, T_1, t,

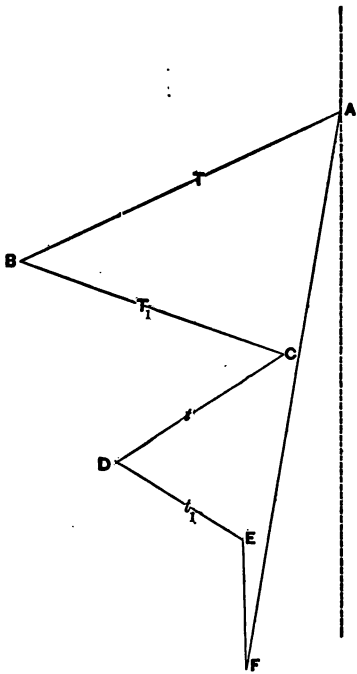
Fig. 33.



and t_1. Draw $E\,F$ vertical and representing on the same scale the weight of wheel and shaft. Then $A\,F$ will on the same scale represent the intensity and

direction of the thrust on the bearings. If we had been considering an end sta-

Fig. 34.



tion the distances *B C* and *D E* would have been zero.

EFFICIENCY.

OTHER things being equal, the *relative* merit of various methods of transmitting power will be indicated by the cost of transmitting a certain amount of power to any given point, as compared with the cost of this power at the generating station, while their *absolute* merit will be shown by comparing the cost of the transmitted power at the receiving station with the cost of producing the required power directly at this point. Such determinations are materially affected by variations in the amounts of power and in the distance of transmission, the other principal factors to be considered being the efficiency of the system, the number of working hours per annum, the price of one horse-power per hour at the generating and receiving stations, and the convenience and applicability of the system to each special case.

The efficiency of any system of trans-

mitting power is expressed by the ratio of the power obtained at the receiving station to the power given out at the generating station. In all systems, losses of power of greater or less magnitude occur, and the most efficient system is that in which those losses are reduced to a minimum.

In the transmission of power by wire ropes, the causes which tend to thus waste a portion of the power in doing useless and even prejudicial work are—

1. The rigidity of the ropes in bending to the curve of the main wheels and carrying-sheaves. (The loss from this source may usually be regarded as insensible; for when the wheels are made sufficiently large, the wires of the rope straighten themselves by their own elasticity after leaving the wheels);

2. The friction of the journals of the wheel-shafts;

3. The resistance of the air to the rotation of the wheels and to the passage of the rope through it.

The friction of the journals varies di-

rectly with the pressure on the bearings, while the resistance of the air depends only on the velocity of the wheels and ropes. The losses due to both these causes have been experimentally determined in a number of cases. It must be noted that, as the pressure on the bearings depends only on the tension and deflection of the rope, which with a given velocity of wheels are constant irrespective of the power transmitted, it follows that these losses are to a large extent independent of the transmitted power. When the direct tension due to the latter is small compared to the tension due to the span and deflection of the rope, these losses will become of considerable *relative* magnitude, so that it is a condition of efficiency that the system shall be worked at the highest suitable power. Under such circumstances, the efficiency of a single pair of stations has been determined to be 0.962 ; so that the efficiency of any whole system including a certain number of intermediate stations is as follows :

Number of Intermediate Stations.	Efficiency of System.	Per cent of Power Wasted.
0	0.962	3.8
1	.944	5.6
2	.925	7.5
3	.908	9.2
4	.890	11.0
5	.873	12.7

The efficiency is thus seen to be very high for ordinary distances, and, for any given distance, it will be greater the fewer the number of intermediate stations.

One of the best recently published comparisons of the four principal systems that may be employed for transmitting power to distances is to be found in Beringer's "Kritische Vergleichung der Elektrischen Kraftübertragung" (Berlin, 1883). On the basis of many experimental determinations, he has computed the following table as representing the commercial efficiency of the different systems under various conditions of distance and power, all the systems being supposed to be working to the best advantage :

COMMERCIAL EFFICIENCY.

Distance of Transmission in feet.	Electric.	Hydraulic.	Pneumatic.	Wire Rope.
300	.69	.50	.55	.96
1,500	.68	.50	.55	.93
3,000	.66	.50	.55	.90
15,000	.60	.40	.50	.60
30,000	.51	.35	.50	.36
60,000	.32	.20	.40	.13

It will be seen from this table that wire rope is most efficient up to about three miles, beyond which electric and pneumatic transmission are most efficient.

The cost of erecting and operating such transmissions varies greatly according to local circumstances. For wire-rope transmissions, the prices of ropes, wheels, and linings previously given will assist in its determination for any special case. In France, where by far the greater number of applications of this method have been made, the average cost of the plant and its erection is estimated at about $1600 per mile, with about $5 per horse-power additional for the necessary constructions at the termini.

Beringer enters at length into the matter of cost, taking up in detail the capital outlay required for various distances and amounts of power, each of the systems being supposed to be worked in the most economical manner.

We need not follow him in the details of his many calculations, in which he considers thoroughly the practical bearings of the subject, but his final conclusions are full of interest.

The following table gives the probable capital outlay required to establish transmission plants under the circumstances given. These figures do not include buildings, boilers, chimneys, and cost of prime mover, as they are taken into account in the cost of producing one horse-power per hour, but include all other expenses.

From this table it will be seen that for distances less than about one mile the cost of the plant for wire-rope transmission is less than that for any other system, and specially so as the power to be transmitted increases in amount. For powers greater than 100 H. P., its cost is

less for any distance not exceeding three miles.

CAPITAL OUTLAY, IN DOLLARS, PER HORSE-POWER.

Maximum Horse-power Transmitted.	Distance of Transmission, in feet.	Electric.	Hydraulic.	Pneumatic.	Wire Rope.
5	300	365	200	355	32
	1,500	380	321	468	151
	3,000	394	472	1,020	297
	15,000	526	1,740	2,920	1,480
	30,000	691	2,970	5,300	3,700
	60,000	1,020	6,230	10,000	5,940
10	300	253	146	292	25
	1,500	263	219	350	112
	3,000	273	317	429	229
	15,000	375	1,070	1,040	1,125
	30,000	502	2,030	1,800	2,240
	60,000	750	3,920	3,310	4,550
50	300	195	78	151	8¾
	1,500	200	102	175	35
	3,000	205	146	205	68
	15,000	268	443	428	336
	30,000	336	828	716	662
	60,000	487	1,580	1,290	1,324
100	300	156	68	127	5½
	1,500	161	97	146	21
	3,000	170	136	166	41
	15,000	219	429	326	200
	30,000	287	799	531	394
	60,000	424	1,510	935	789

In comparison with electric transmission, which is practically its only competitor for long distances, we have

already seen that, while the commercial efficiency of wire ropes is much greater than than that of electric transmission for short distances, it rapidly falls and becomes less than that of the latter as the distance increases. The true comparison of the various systems must of course involve both capital outlay and commercial efficiency; in other words, the figure of merit for each system is the price which must be paid for one horse-power at the receiving station.

To obtain this price, the assumption is made that the average cost of one horse-power per hour at the operating station is in

Steam-engines of more than 50 H.P. . 2.07 cts.
" " " from 10 to 50 H.P. . 5.84 cts.
" " " less than 10 H.P. . 7.71 cts.

while the average cost of one horse-power in water-power varies from 0.2 to 0.4 cent per hour.

Taking into account the figures for efficiency previously given, and allowing 14 per cent of the capital outlay for interest and depreciation, the following tables represent the cost of power at the

receiving station, the power transmitted being supposed in each case to be generated at the cheapest of the above rates :

STEAM-POWER TRANSMITTED.

PRICE, IN CENTS, OF ONE HORSE-POWER PER HOUR AT RECEIVING STATION.

Maximum Horse-power Transmitted.	Distance of Transmission, in feet.	Electric.	Hydraulic.	Pneumatic.	Wire Rope.
5	300	4.6	5.1	5.5	2.3
	1,500	4.7	5.8	6.0	2.9
	3,000	4.9	6.4	6.7	3.8
	15,000	5.8	13.2	10.6	11.0
	30,000	6.7	21.3	19.3	21.1
	60,000	10.5	38.5	33.9	46.0
10	300	4.0	4.8	5.1	2.3
	1,500	4.2	5.2	5.4	2.8
	3,000	4.3	5.7	5.8	3.5
	15,000	5.1	10.3	9.1	9.1
	30,000	6.3	15.6	12.7	17.2
	60,000	9.8	29.0	21.1	38.7
50	300	3.8	3.3	4.1	2.2
	1,500	3.9	3.4	4.3	2.4
	3,000	4.0	3.6	4.4	2.6
	15,000	4.6	5.9	5.8	5.1
	30,000	5.6	8.5	7.2	9.1
	60,000	8.6	15.8	10.7	22.5
100	300	3.6	3.3	4.0	2.2
	1,500	3.7	3.4	4.1	2.3
	3,000	3.9	3.6	4.2	2.5
	15,000	4.4	5.8	5.3	4.5
	30,000	5.3	8.4	6.3	7.8
	60,000	8.3	13.9	9.1	19.7

WATER-POWER TRANSMITTED.

PRICE, IN CENTS, OF ONE HORSE-POWER PER HOUR AT RECEIVING STATION.

Maximum Horse-power Transmitted.	Distance of Transmission, in feet.	Electric.	Hydraulic.	Pneumatic.	Wire Rope.
5	300	0.71	0.59	0.81	0.22
	1,500	0.73	0.77	0.95	0.38
	3,000	0 75	0.97	1.17	0.61
	15,000	0.89	2.79	2.57	2.53
	30,000	1.05	5.06	4.86	5.06
	60,000	1.70	9.70	9.01	9.84
10	300	0.54	0.50	0.71	0.18
	1,500	0.56	0.61	0.77	0.34
	3,000	0.58	0.75	0 89	0.50
	15,000	0.73	1 92	1.78	1.94
	30,000	0.95	3.12	2.88	3.87
	60,000	1.44	6.42	8.04	8.10
50	300	0.46	0.30	0.44	0.18
	1,500	0.48	0.36	0.48	0.22
	3,000	0.52	0.44	0.56	0.26
	15,000	0.58	0.98	0.89	0.77
	30,000	0.62	1.54	1.31	1.46
	60,000	1.11	2.89	2.19	3.26
100	300	0.40	0.32	0.44	0.16
	1,500	0.44	0 34	0.46	0.20
	3,000	0.46	0 38	0.48	0.22
	15,000	0.52	0.87	0.73	0.56
	30,000	0.65	1.46	0 97	0.97
	60,000	1.01	2.31	1.66	2.40

From the foregoing tables (which are substantially as given by Beringer) it appears that the hydraulic and pneumatic systems are not the *cheapest* in any of the cases considered; and the conclusion

seems tc be that they are not suitable for long-distance transmission, except in cases where special circumstances prevent the use of either electricity or wire rope, or where the water or air may be of further use after being discharged. Thus the pneumatic method is specially adapted for use in tunnels, where it answers the double purpose of driving the machinery and ventilating the tunnel. On board war-ships, it has similar advantages, with the further one that the fracture of a pipe during action will not, by the discharge of water or steam under pressure, produce injurious results on the men in the vicinity.

Except in unusual cases, it would always be more economical to place a local steam-engine if the power from it can be had at a cheaper rate than it can be brought from a distant source. If this source be water-power, then the local engine is more expensive in all the cases considered; but if the source be a large steam-engine, the question of relative economy hinges on the distance and the amount of power.

In considering the foregoing tables, it must be noted that considerable reductions in the price of dynamos and motors have been made since they were computed (1883); so that the showing should be somewhat more in favor of the electric system than the tables give it.

A careful study of the tables, bearing in mind the fact just stated, and the costs of producing the power in various sizes of engines previously given, leads to the following conclusions, within the limits of power and distances given in the table, the question of economy only being considered:

It pays to transmit cheap water-power without regard to the amount of power or the distance; and it pays to transmit cheap steam-power, provided the amount of energy required at any receiving station does not exceed about ten horse-power and the distance is not greater than about three miles.

In all cases, wire-rope transmission is the cheapest for distances less than about three quarters of a mile; beyond that

distance, electric transmission is the cheapest.

Of course, as suggested before, the question of convenience may be more important than that of economy ; in which case the system of electric transmission, especially in the vicinity of the large generating stations in our great cities, will usually be found preferable for even shorter distances than the limit above given.

HISTORICAL SKETCH.

THE first transmission was put up by the brothers Hirn in 1850, at a calico weaving establishment near Colmar. An immense mass of scattered buildings seemed to forbid the possibility of using them and yet placing the motive power at any one point. In this emergency, they first tried this method of power transmission, using a riveted steel ribbon to each building from the engine-house. The steel bands were about $2\frac{1}{2}$ inches wide by 0.04 inch thick, and ran on wood-faced drums. This presented two inconveniences. In the first place, on account of its considerable surface, the band was liable to be agitated by the wind; and secondly, it soon became worn and injured at the points where it was riveted. It served, however, very well for eighteen months to transmit twelve horse-power to a distance of 250 feet. The success of the prin-

ciple was complete, but much remained to be done before the wire rope and the rubber or leather-lined driving-wheel solved all difficulty and made this method of transmitting power practically successful.

The number of applications has increased very rapidly. At the end of 1859, there were but few applications in use; in 1862, there are known to have been about 400, and in 1867 about 800. At the present time there are thousands in successful operation. In 1864, a terrible explosion destroyed almost all of the great powder-mill at Ockhta, situated about six miles from St. Petersburg. The whole establishment was rebuilt. After studying many combinations, an artillery officer proposed to profit by the resources which this method offered to engineers, and thus to realize the only combination which could prove successful in a powder-mill; namely, great distance between the buildings, so that the explosion of one should not entail the ruin of the rest. The new establishment, which went into operation in 1867, is com-

posed of thirty-four different workshops or laboratories, to which motive power is transmitted by means of wire ropes driven by three turbines, thus distributing a total of 274 horse-power along a line nearly a mile in length.

One of the largest transmissions is that employed to utilize the falls of the Rhine near Schaffhausen, in Switzerland. Advantage was taken of the rapids at one side, to put in a number of turbines, but since the steep, rocky banks forbade the erection of any factories in the immediate vicinity, the entire power was transferred diagonally across the stream to the town, more than half a mile farther down, and there distributed, certain rocks in the water being made use of to set up the required intermediate stations.

There are three turbines giving out collectively about 700 horse-power. There are two wheels fifteen feet in diameter, keyed on a horizontal shaft running over the three turbines and geared with them all. Two wire ropes, $\frac{3}{4}$ inch in diameter, run right across the river,

a distance of 370 feet. Here two secondary wheels are fitted, which drive two secondary ropes running up the banks of the river for a distance of 1500 feet, this distance being subdivided into three lengths. From the end station about 400 horse-power are transmitted to a farther distance of 1500 feet; so that the total length of rope transmission amounts to 3370 feet.

Another very large and interesting transmission was erected in 1872 at Bellegarde,* a small town near the confluence of the Rhone and a mountain torrent called the Valserine, about fifteen miles from Geneva. The total disposable horse-power is estimated at 12000, of which only about one fourth has been utilized. This power is obtained by means of six Jonval turbines, each of 630 horse-power; and it is transmitted from each turbine by a pair of ropes running side by side, so connected by differential gear as to close the sluice of the turbine in case a rope should break.

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* See "Engineer," vol. 37, 1874.

The wheels are 18 feet in diameter, and make 70 revolutions per minute, giving the rope a velocity of 3920 feet. The ropes are 1¼ inch in diameter. The power from the different turbines is transmitted in different directions.

Among other industries at Bellegarde thus supplied with power, an interesting case is that of a phosphate-mill, which receives about 300 horse-power by means of a pair of ropes. The turbines are down in a ravine, so that each rope first run upwards at a steep inclination over a pair of carrying-sheaves (Plate I), whose vertical and horizontal distances from the lower wheel are 116 and 197 feet respectively; and then round a wheel at the first intermediate station (Plate II) at a further distance of 430 feet. Then follow other stations at distances of 426, 426, 571, 290, and 634 feet, making a total of 2974 feet.

The object of running the inclined rope over the carrying-sheaves and through to the second station is to give the inclined portions the requisite tension, as previously explained.

Examples might be multiplied, but the above are sufficient to illustrate the extent of the practical applications of this method of transmitting power, which by its low cost of erection and maintenance, and its high efficiency, has demonstrated its undoubted superiority, from an economic standpoint, over all other systems of transmitting power, for distances ranging from 100 to 3500 feet.